ATLAS 硅径迹探测器升级结题报告

朱宏博

2021年8月27日

参加单位：中科院高能物理研究所、清华大学

报告提纲

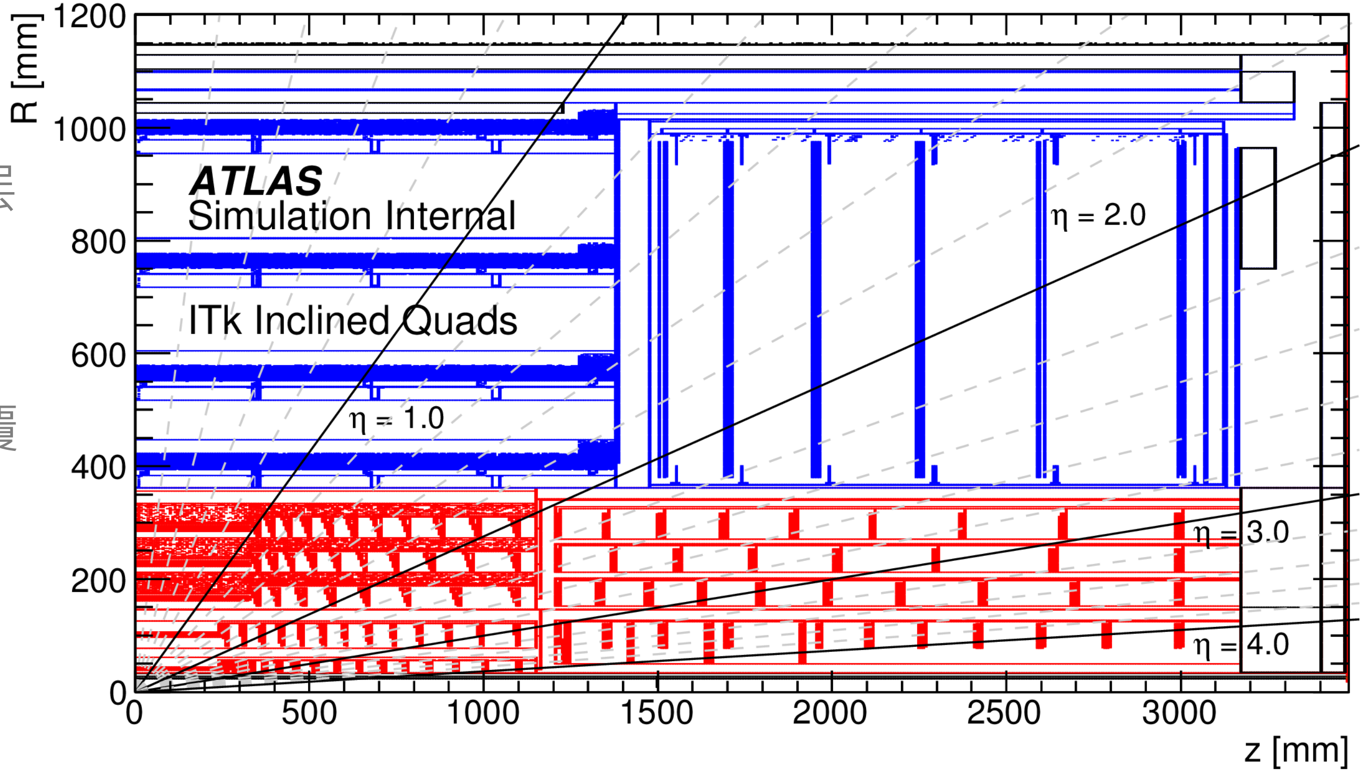
- 项目背景
- 课题任务、目标和考核指标
- 研究内容、主要技术突破和创新
- 课题完成情况和主要成果
- 经费执行情况
- 总结

项目背景

ATLAS 硅径迹探测器升级

- 应对大型强子对撞机高亮度升级（HL-LHC），保持甚至提升径迹探测性能，建造全硅径迹探测器（Inner Tracker）→ 领域内最前沿的硅探测器和电子学技术

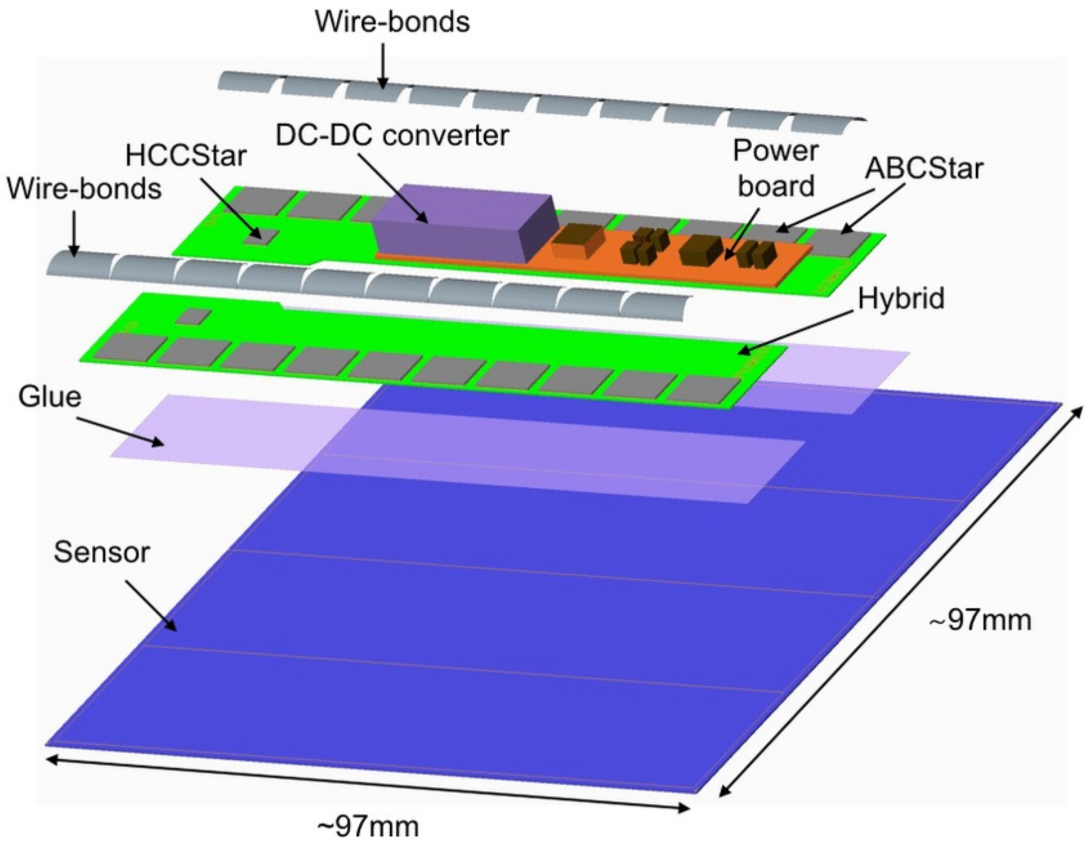
中国组（高能所、清华大学）参与外层硅微条探测器桶部项目（ITk-Strip）。向ATLAS合作组贡献1，000个探测器模块，约占桶部模块总数的10%，硅覆盖面积近10 m²。

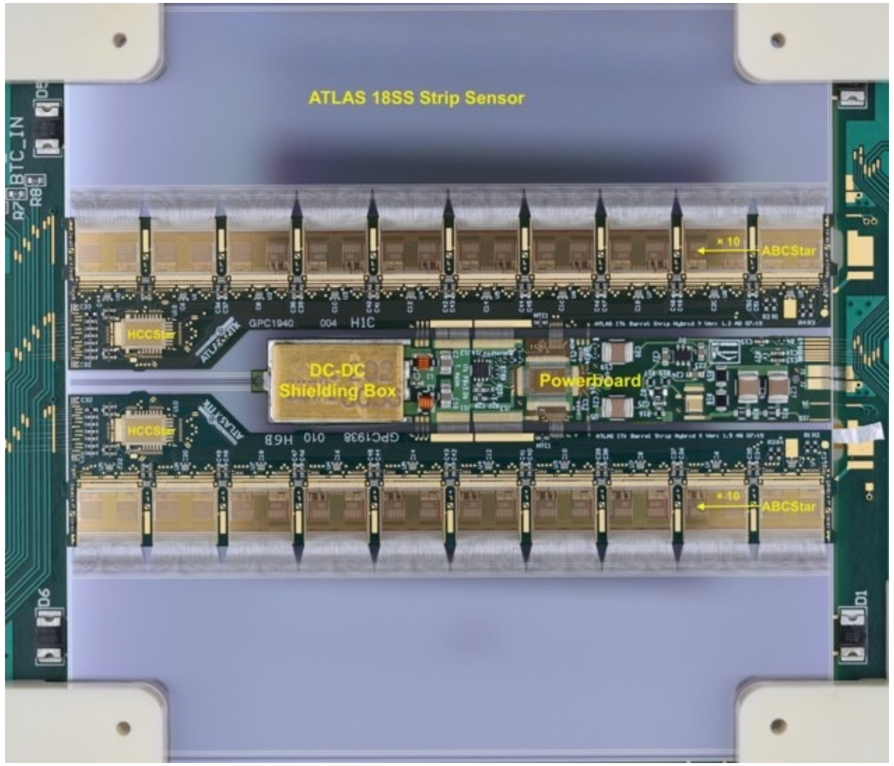


硅微条探测器模块

ITk-Strip 探测器最基本单元

- 基本组件：SS/LS 硅微条传感器、前端读出芯片、电源管理芯片等





课题任务、目标

- 围绕硅微条探测器模块，定义课题主要研究任务：
  - 前端读出电子学ASIC设计 → 基准设计方案，高速、抗辐照数字电路设计
  - 硅微条探测器模块设计 → 承担最终建造任务，原理样机 → 工程样机 → 小批量生产
  - CMOS硅微条探测器性能研究 → 前沿新技术研究

- 主要目标：通过参与高性能硅探测器研制项目，积极开展国际合作，掌握硅探测器制作基本工艺流程，积累研发经验。

考核指标

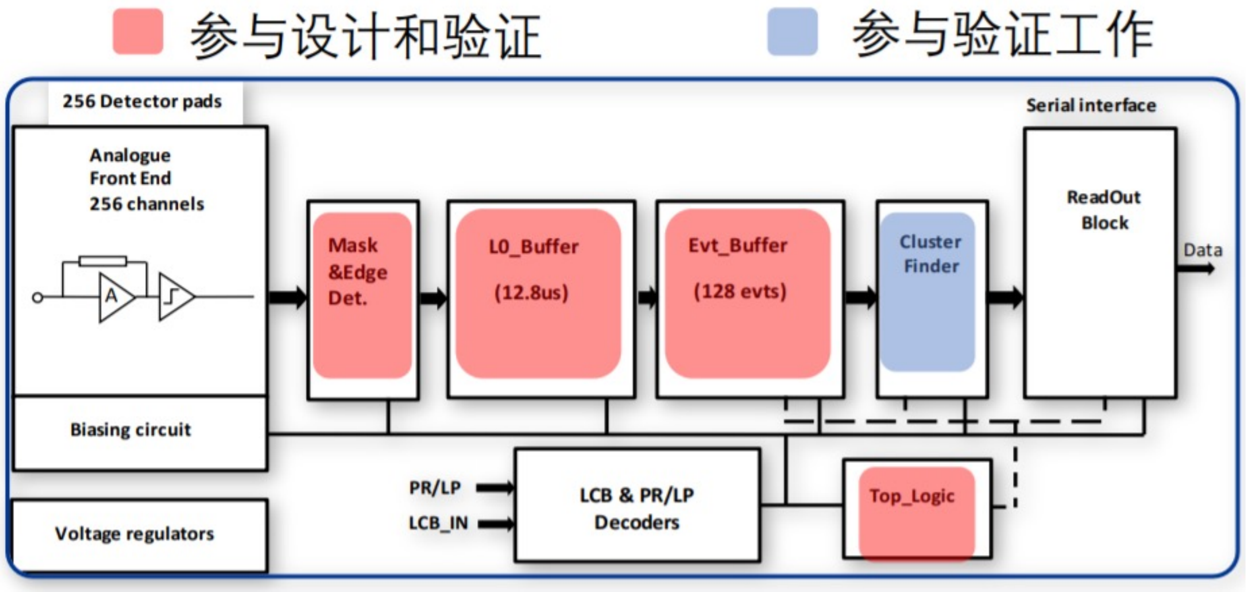
任务书指标

课题目标[1]	成果名称	成果类型	考核指标[2]				考核方式（方法）及评价手段[4]
			指标名称	立项时已有指标值/状态	中期指标值/状态[3]	完成时指标值/状态	
（限 500 字以内。）研制成功具有高空间分辨、抗辐照的硅微条探测器（包括前端电子学 ASIC 芯片），完成至少 50 个科工作的硅微条探测器模块；完成 CMOS 硅微条探测器性能研究。	1：硅微条径迹探测器模块	□新理论 □新原理 □新产品 □新技术 □新方法 □关键部件 □数据库 □软件 □应用解决方案 ■实验装置/系统 □临床指南/规范 □工程工艺 □标准 □论文 □发明专利 □其他	硅微条探测器模块空间分辨率，抗辐照性能	无	无	25 微米 1.6×10^{15} 1MeV n_{eq}/cm^2	性能指标通过放射源测试，由 ATLAS 合作组安排束流测试。
	2：CMOS 硅微条探测器模块	□新理论 □新原理 □新产品 □新技术 □新方法 □关键部件 □数据库 □软件 □应用解决方案 ■实验装置/系统 □临床指南/规范 □工程工艺 □标准 □论文 □发明专利 □其他	CMOS 硅微条探测器模块空间分辨率，抗辐照性能	无	无	25 微米 1.6×10^{15} 1MeV n_{eq}/cm^2	性能指标通过放射源测试，由 ATLAS 合作组安排束流测试。

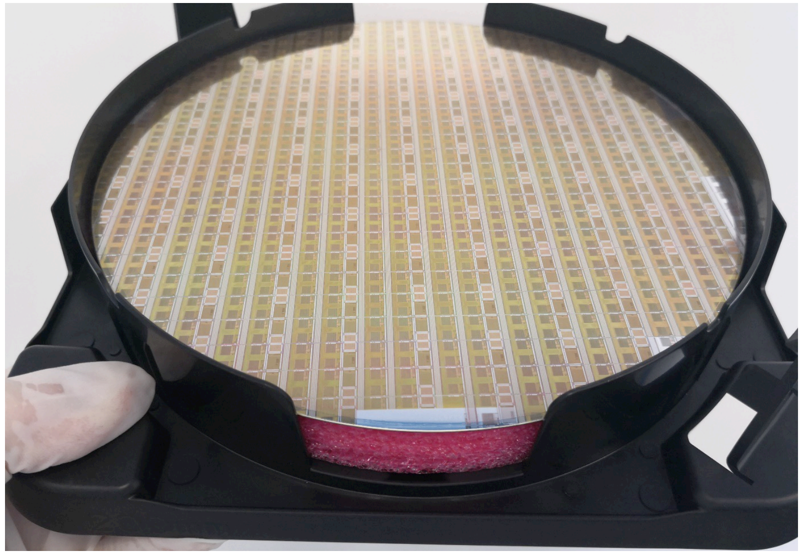
一、前端读出电子学ASIC设计

基准设计方案

- ABC-STAR芯片：新数据读出方式匹配更高L0触发率，重点设计后端数字，提升模拟前端性能→ 与CERN及宾夕法尼亚大学合作，GF/IBM 130 nm CMOS 工艺
    - 主要贡献：输入寄存、指令流水线、触发缓存、信号输出等数字逻辑功能模块，基于SystemVerilog搭建验证平台



W. Lu et al, 2017 JINST 12 C04017



经过设计迭代，芯片已通过最终评审（FDR），获准投入量产；

后续工作：芯片抗辐照性能研究

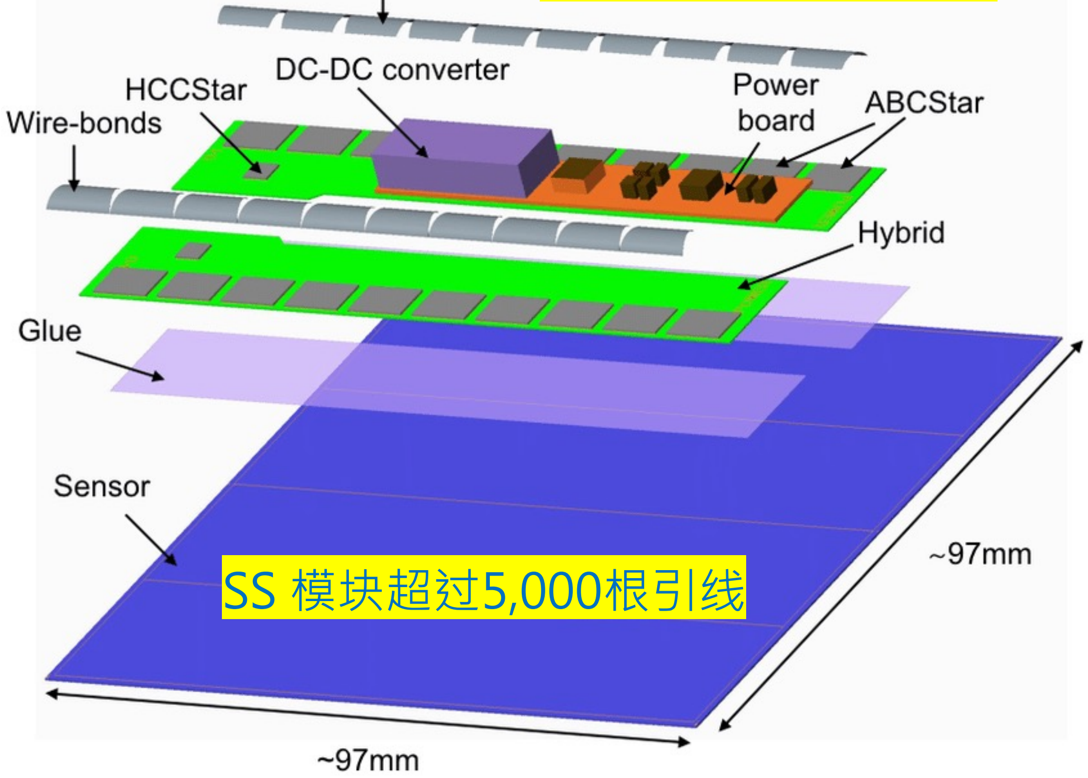
二、硅微条探测器模块设计

承担最终建造任务

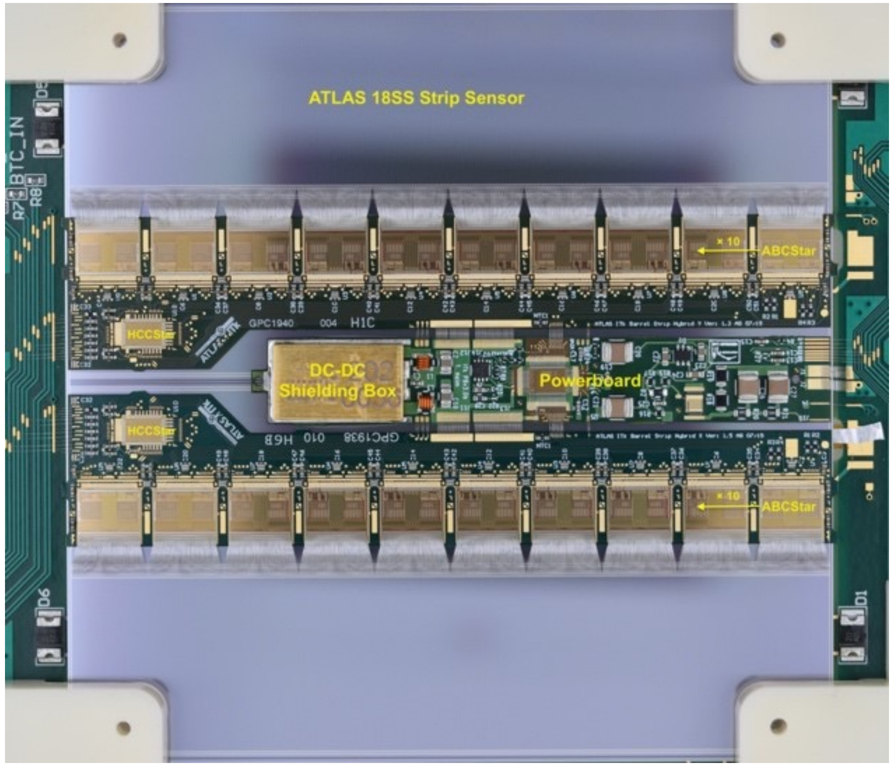
技术设计报告ATLAS-TDR-025，2020 JINST 15 P09004

- 硅微条径迹探测器基本单元，包含SS/LS 硅微条传感器、前端读出芯片（ABC-STAR）、控制芯片（HCC-STAR）、电源管理芯片（AMAC）等

电子学通道数：5,120



SS 模块超过5,000根引线



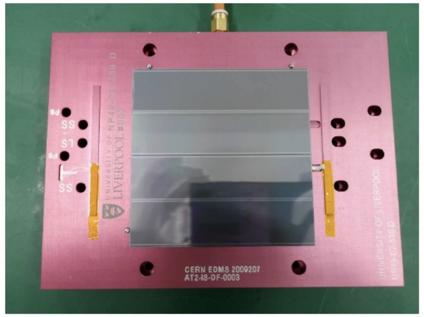
工艺流程

质量控制、质量确认

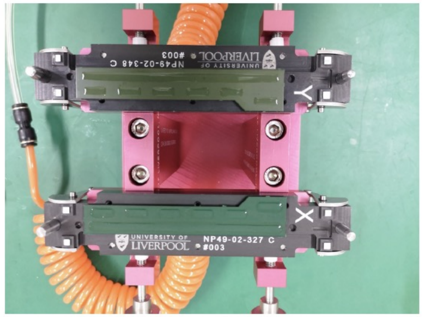
- 实现完整工艺流程（质量控制、质量确认），确保探测器模块实现设计性能

部分步骤

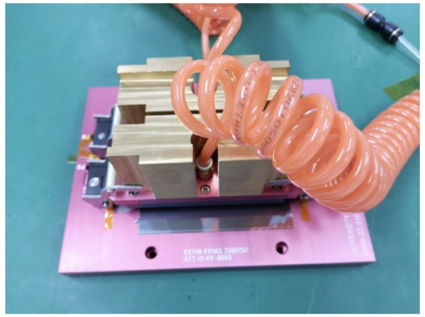
- Align Sensor on sensor plate



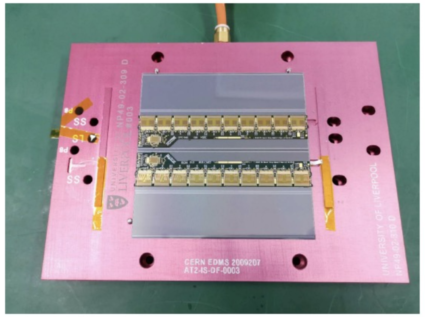
- Dispense glue on Hybrid through Stencil



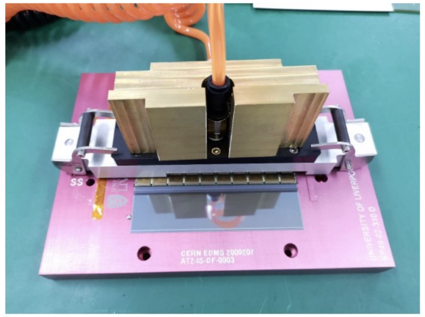
- Glue Hybrids on sensor



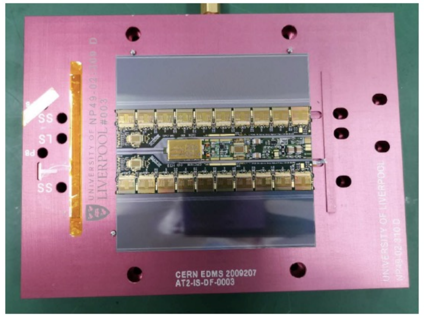
- Module without Powerboard

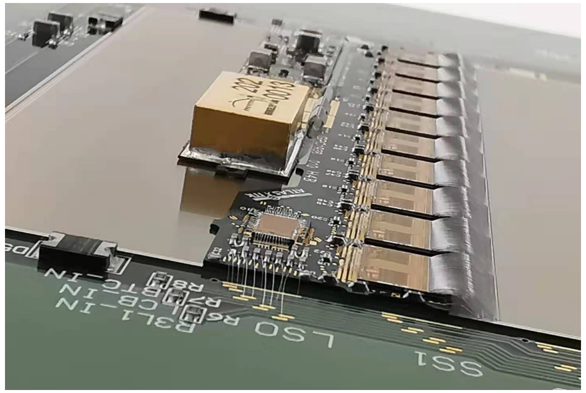


- Glue Powerboard to sensor

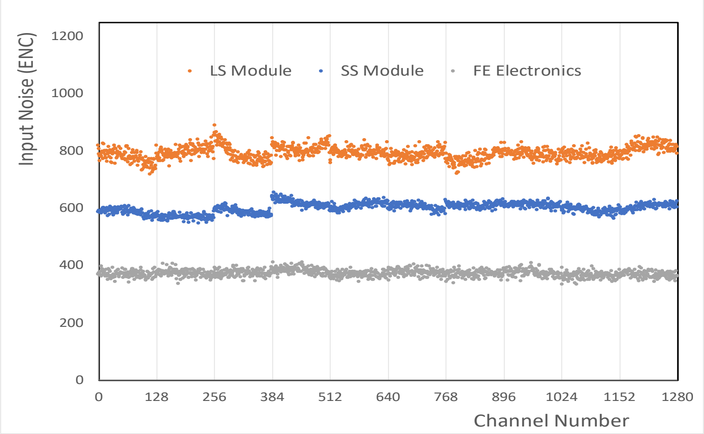


- Assembled Module





四层高密度引线键合

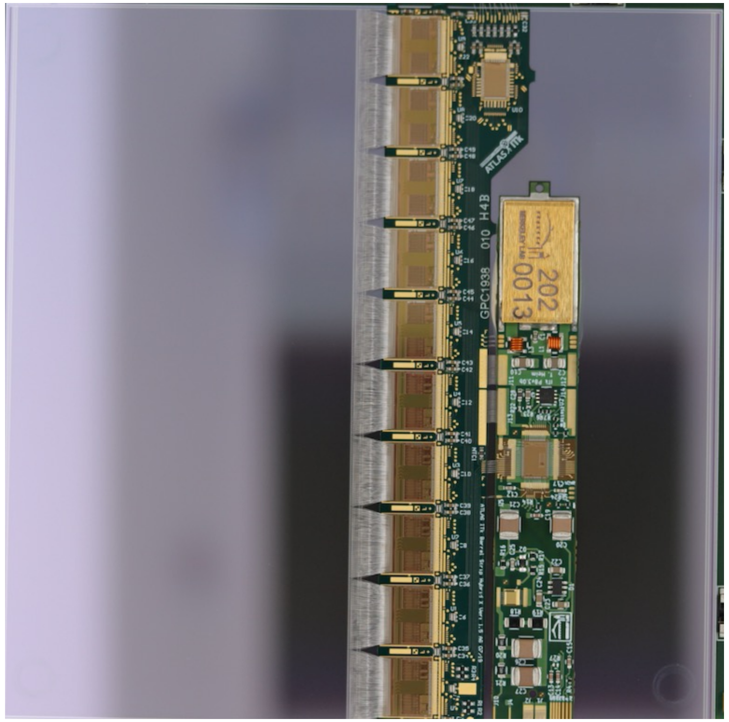


引线前后噪声水平变化

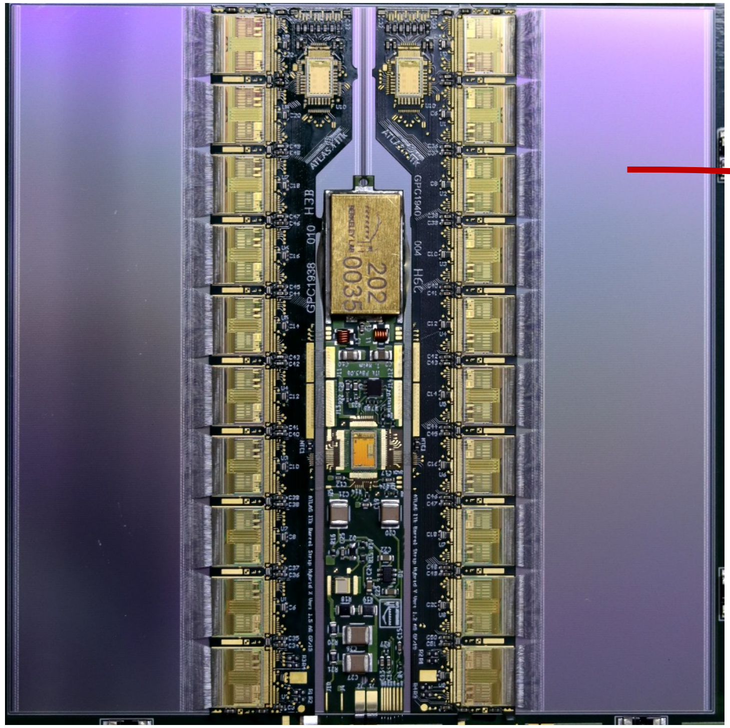
成功试制模块样机

LS/SS模块

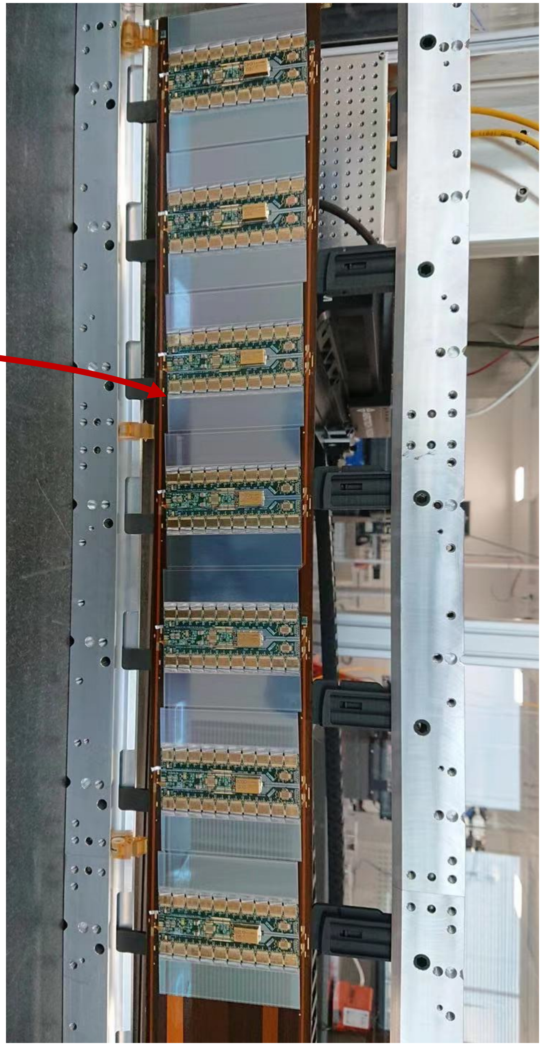
SS 模块已运往英国卢瑟福实验室，用于FDR桶板建造



LS 探测器模块 (2/3 + 2)



SS 探测器模块 （ 3/3 ）



同时在RAL实验室合作完成超过20个探测器模块！

芯片禁运问题

- 芯片禁运对开展项目研究（芯片设计、模块样机研制等）存在诸多限制；
- 经过长期持续沟通，最终通过欧洲核子中心（CERN）成功申请到美国商务部出口许可，获得芯片用于原型样机。二次申请芯片覆盖多个升级项目，高能所-CERN协议（编号：KN4809IEP）；

Re-Export License
D1087861
Validated: April 07, 2017
Expires: April 30, 2024

UNITED STATES DEPARTMENT OF COMMERCE
BUREAU OF INDUSTRY AND SECURITY
WASHINGTON, D.C. 20230

Unless limited by a condition set forth below, the export, reexport or transfer (in-country) authorized I
is for the item(s), end-use(s), and parties described in the license application and any letters of expla
applicant is responsible for informing the other parties identified on the license, such as ultimate con
end-users, of the license's scope and of the specific conditions applicable to them. BIS has granted t
in reliance on representations the applicant made in the license application, letters of explanation, ar
documents submitted.

Applicant Reference Number: CER0007

Re-Export License
D1177529
Validated: November 18, 2019
Expires: November 30, 2025

UNITED STATES DEPARTMENT OF COMMERCE
BUREAU OF INDUSTRY AND SECURITY
WASHINGTON, D.C. 20230

Unless limited by a condition set forth below, the export, reexport or transfer (in-country) authorized by this license is for the item(s), end-use(s), and parties described in the license application and any letters of explanation. The applicant is responsible for informing the other parties identified on the license, such as ultimate consignees and end-users, of the license's scope and of the specific conditions applicable to them. BIS has granted this license in reliance on representations the applicant made in the license application, letters of explanation, and other documents submitted.

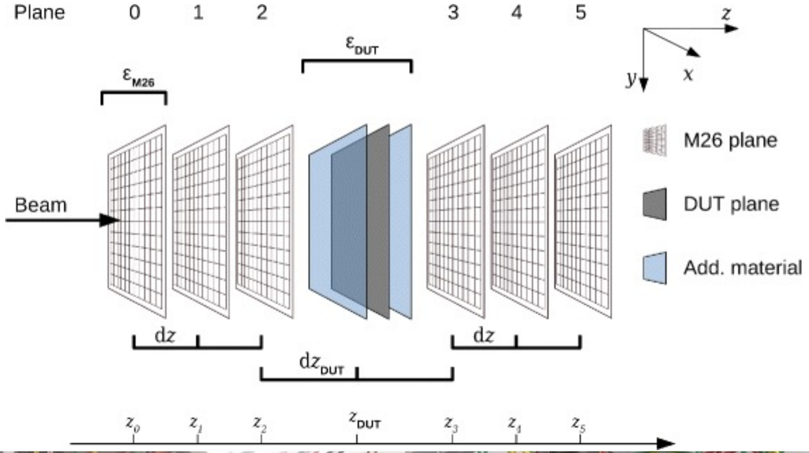
Applicant Reference Number: CER0010

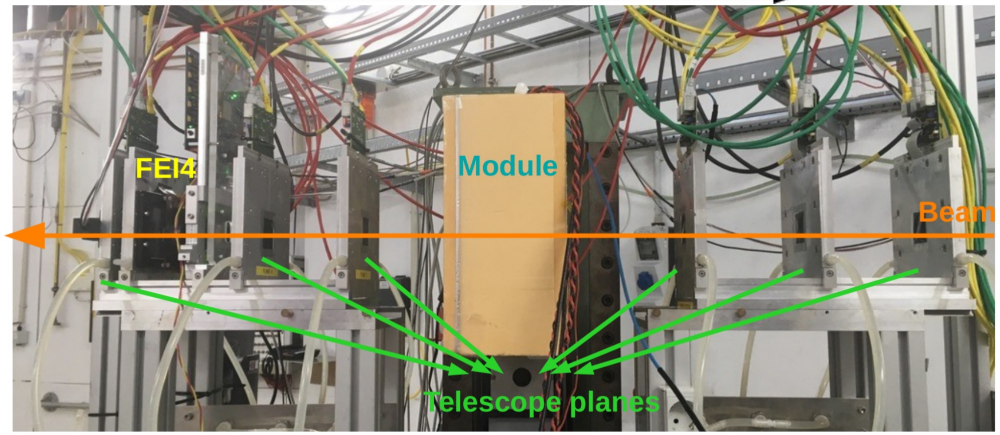
束流测试

位置分辨率、探测效率等

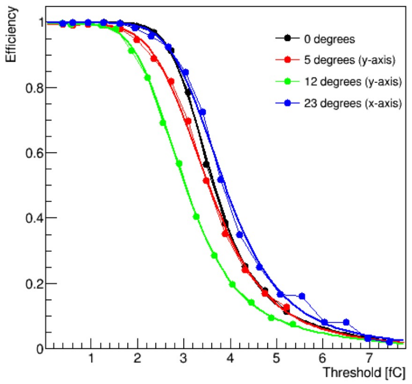
NIMA V924 (2019) 108-111、NIMA V979 (2020) 164430

- 探测器研发关键步骤，标定探测器位置分辨率、探测效率等，测试数据获取系统（最接近实验的运行环境）

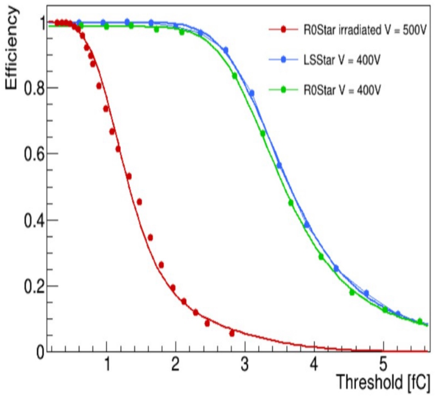




电荷随入射角度变化



辐照前后阈值变化



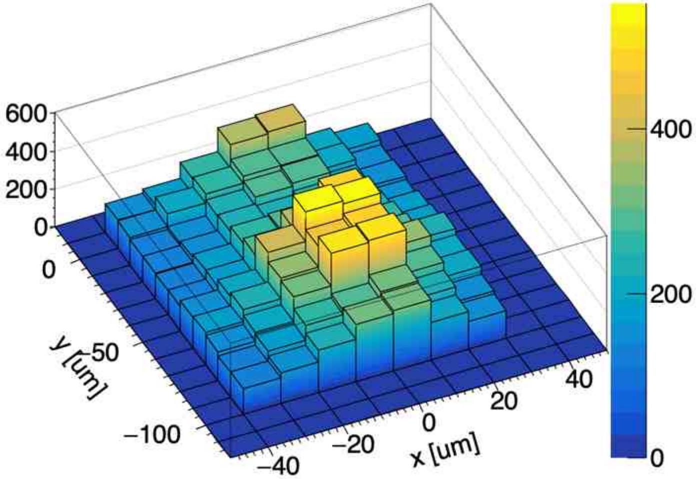
- 主要贡献：
  - 现场技术支持、试验取数值班
  - 离线重建软件开发：EUTelescope、新软件框架 Corryvreckan
  - 端盖模块坐标转换算法
  - 桶部模块数据分析 → module FDR

三、CMOS硅微条探测器性能研究

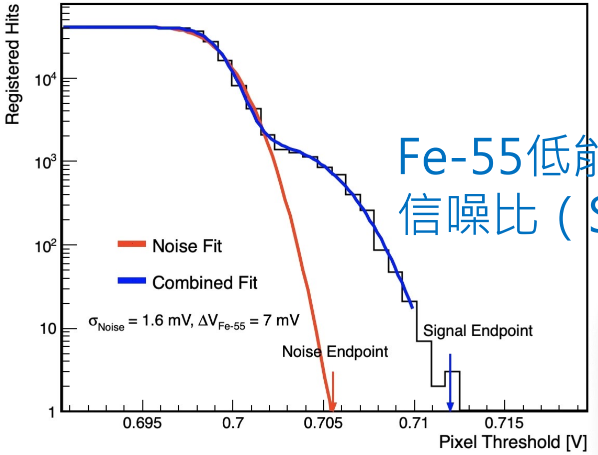
前沿新技术研究

Y. Han, et al., NIMA 981 (2020) 164520

- 新型CMOS传感器作为备选方案，基于高压/高阻CMOS工艺研制一体式硅探测器。但由于项目时间紧迫，最终未采用



电极/像素间距与设计值相符（20/40 um）



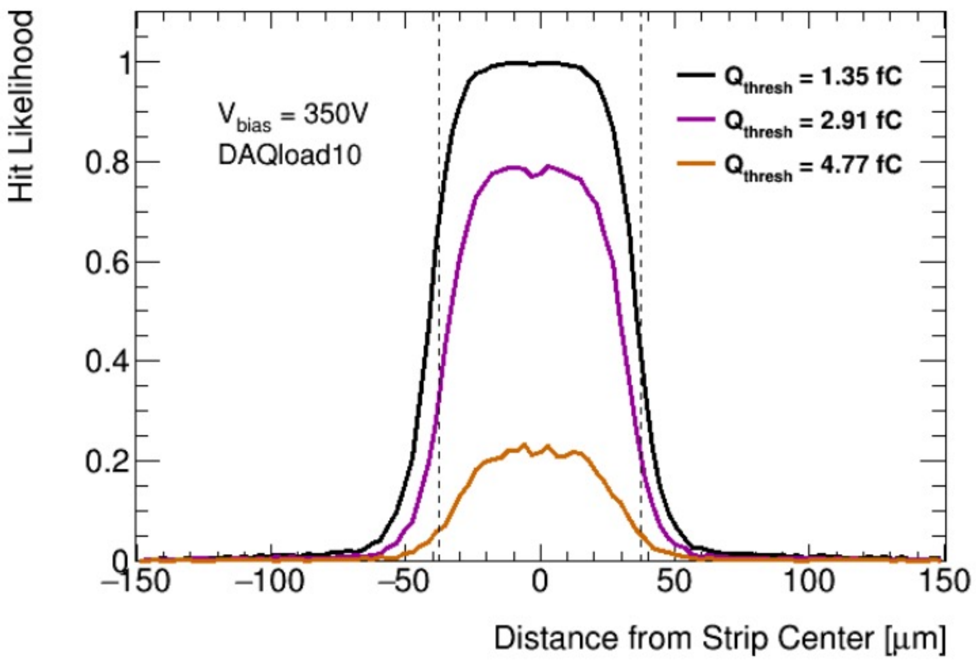
Fe-55低能光子（5.9 keV），信噪比（S/N）~3

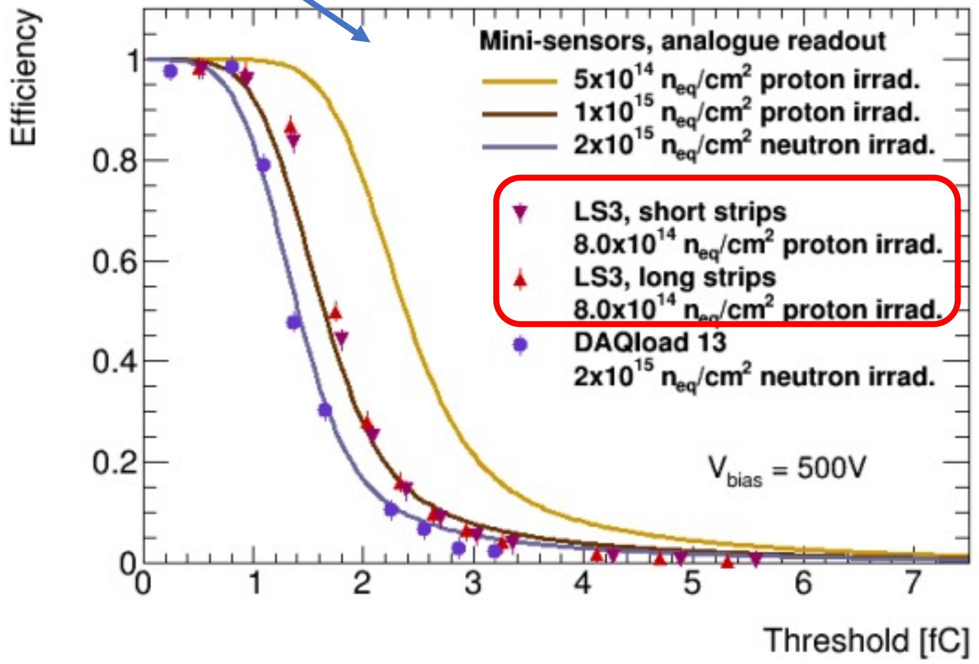
任务完成情况

技术设计报告ATLAS-TDR-025，2020 JINST 15 P09004

- 1. 硅微条探测器模块 → 合作组统一安排中子及质子辐照，电子束流测试
  - 考核指标：1. 空间分辨率好于25微米，2. 抗辐照性能好于1.6×10^{15} 1 MeV n_{eq}/cm^2
  - 中期指标调整：抗辐照性能好于 0.8×10^{15} 1MeV n_{eq}/cm^2 ，合作组重新计算抗辐照要求，探测器研发按照新的指标开展。

微条间距~75微米，位置分辨率好于25微米

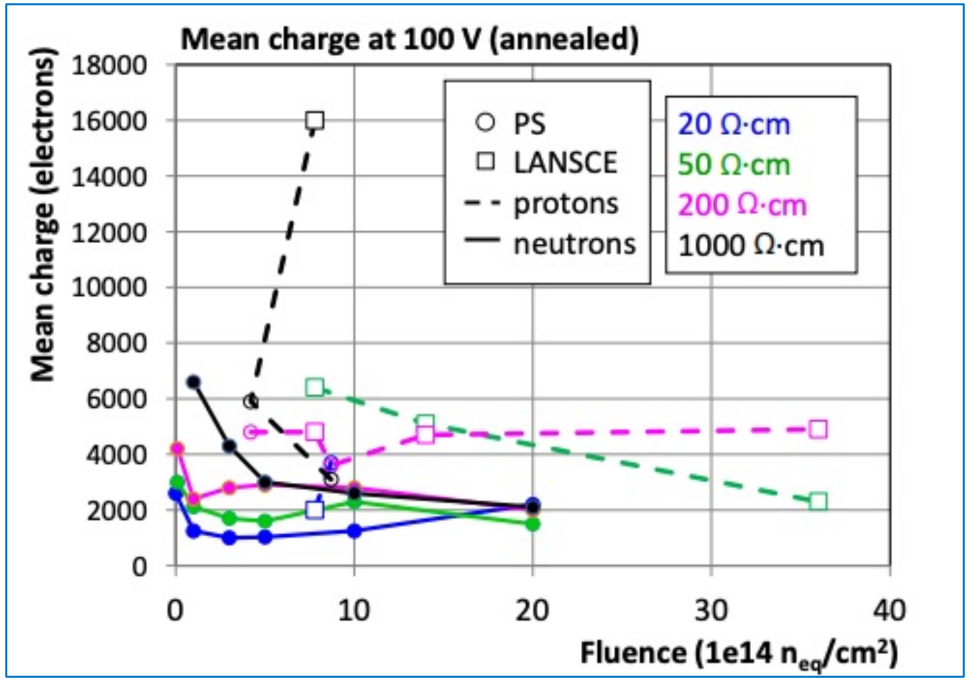




任务完成情况

ATLAS ITk

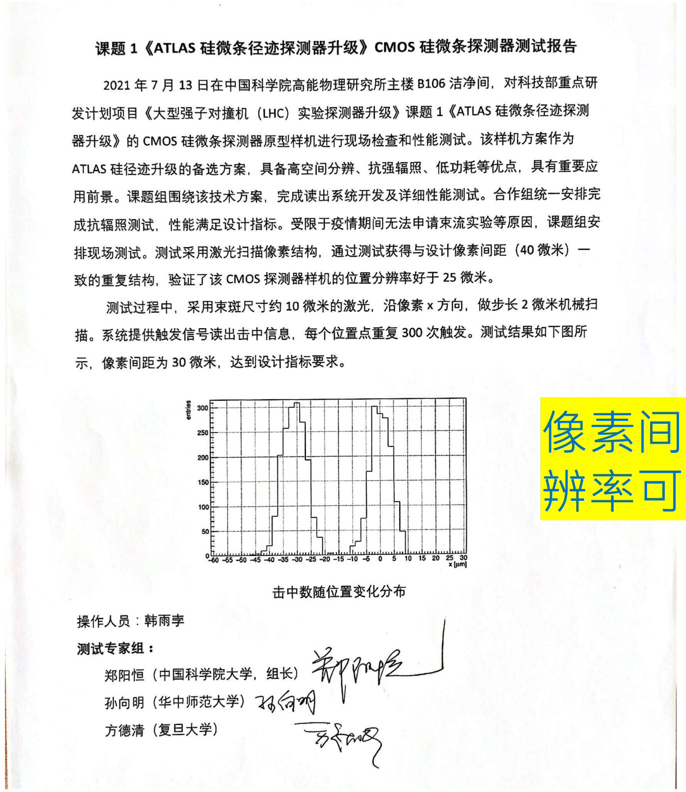
- 2. CMOS硅微条探测器模→ 合作组统一安排中子及质子辐照
  - 考核指标：1. 空间分辨率好于25微米，2. 抗辐照性能好于1.6×10^{15} $1\mathrm{MeV}\ n_{eq}/\mathrm{cm}^2$



采用晶圆电阻率 200欧姆 的传感器在经受$2\times10^{15}/\mathrm{cm}^2$等效中子通量辐照后，SR-90测试信号幅约为5,000个电子，满足探测器设计要求

（NIMA V924 （2019）214-218）

位置分辨率改用激光扫描结构，安排专家现场测试



课题 1《ATLAS 硅微条径迹探测器升级》CMOS 硅微条探测器测试报告

2021 年 7 月 13 日在中国科学院高能物理研究所主楼 B106 洁净间，对科技部重点研发计划项目《大型强子对撞机（LHC）实验探测器升级》课题 1《ATLAS 硅微条径迹探测器升级》的 CMOS 硅微条探测器原型样机进行现场检查和性能测试。该样机方案作为 ATLAS 硅径迹升级的备选方案，具备高空间分辨、抗强辐照、低功耗等优点，具有重要应用前景。课题组围绕该技术方案，完成读出系统开发及详细性能测试。合作组统一安排完成抗辐照测试，性能满足设计指标。受限于疫情期间无法申请束流实验等原因，课题组安排现场测试。测试采用激光扫描像素结构，通过测试获得与设计像素间距（40 微米）一致的重复结构，验证了该 CMOS 探测器样机的位置分辨率好于 25 微米。

测试过程中，采用束斑尺寸约 10 微米的激光，沿像素 x 方向，做步长 2 微米机械扫描。系统提供触发信号读出击中信息，每个位置点重复 300 次触发。测试结果如下图所示，像素间距为 30 微米，达到设计指标要求。

击中数随位置变化分布

操作人员：韩雨李

测试专家组：

郑阳恒（中国科学院大学，组长）

孙向明（华中师范大学）

方德清（复旦大学）

像素间距小于40微米，分辨率可以满足设计要求

合作组支持信

UNIVERSITY OF CALIFORNIA, SANTA CRUZ

BERKELEY • DAVIS • IRVINE • LOS ANGELES • MERCED • RIVERSIDE • SAN DIEGO • SAN FRANCISCO — SANTA BARBARA • SANTA CRUZ

SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS
1156 HIGH ST
SANTA CRUZ, CALIFORNIA 95064

18th August 2021

Letter of Support for IHEP and Tsinghua University

I am writing this letter of support to confirm the contributions made by Tsinghua University and the Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences to the Strip Upgrade project for the HL-LHC ATLAS as well as the related the CHESS II MAPs demonstrator. My name is Dr. Anthony Allen Affolder. I am a Senior Scientist working at the Santa Cruz Institute of Particle Physics (SCIPP) and an Adjunct Professor at the University of California at Santa Cruz, California, USA. Since Oct 2017, I have been the international Strip Project Leader for the HL-LHC upgrade of ATLAS experiment at CERN.

In order to cope with the high instantaneous luminosity and large total integrated fluence, the ATLAS Inner Detector has to be replaced with an all-silicon tracker (ITk), where the sensitive elements are pixelated in the nearer the interaction region and has longer strips (74.5 micron wide and 2-5 centimeters long) in the other region. IHEP and Tsinghua University have been making important contributions to the Strip Barrel working predominantly with RAL in the United Kingdom.

The team has made contributions to the understanding of the radiation tolerance of the readout ASICs (ABCStar) both at RAL and in China. Most of IHEP and Tsinghua University teams' focus has been on strip module assembly and testing. At RAL, they have participated in the assembly and testing of over 20 prototype modules, meeting all contributions expected from the team to RAL. Taking the expertise developed back to China, the team has assembled and tested 5 long strip (LS) and 3 short strip (SS) modules at IHEP. These have been successfully sent back to RAL and integrated into prototype staves.

The plans for pre-production have been impacted by COVID across the entire project, delaying the availability of components and modifying significantly the process of site qualification. This process is where sites become approved to proceed to pre-production at full speed by the Strip project. IHEP has taken a leadership role in these preparations, contributing to both RAL being the 2nd most advanced site in the project towards qualification as well as progressing IHEP's readiness as expected. Without the impact of COVID, there is a high-likelihood that IHEP would have already delivered their commitment of 50 pre-production modules. Ultimately during production, IHEP/Tsinghua will assemble 500 modules in China and another 500 modules in the UK working at RAL. These deliverables are critical to the success of the Strip project, and it is only possible to the commitment and quality of the staff from IHEP and Tsinghua University.

The prototype modules meet the design requirements of better than 25-micron spatial resolution and a radiation tolerance higher than 8×10^{14} 1 MeV n_{eq}/cm^2, as shown by test beam studies of components irradiated to the end-of-lifetime fluence including an additional 50% safety margin. These results were presented at our successful Module Final Design Review.

In parallel, IHEP and Tsinghua have been contributing to the evaluation of the CHESS-2 ASICs, collaborating with SLAC and SCIPP; the CHESS-2 is a demonstrator of MAPs-technology with a strip-like architecture. Prototype sensors have demonstrated that signal could be measured after the targeted 1.2×10^{15} 1 MeV n_{eq}/cm^2 fluence. The position resolution targeted have been demonstrated using laser scanning techniques. Due to COVID restrictions, they were unable to measure the resolution in the test beam. This is a very important milestone, as it shows MAPs-based technology is a viable alternative to the standard; as systems become larger, the cost and time savings of MAPs-based Strips may be an enabling technology to future detectors.

Please feel free to contact me if you have any further questions.

Sincerely,

Dr Anthony Affolder
Senior Research Scientist and Adjunct Professor
Project Leader of the ATLAS Strip Upgrade
Santa Cruz Institute of Particle Physics
University of California, Santa Cruz

ATLAS ITk-Strip Project Leader
Dr. Anthony Affolder 的支持信

文章发表、会议报告

ATLAS ITk

1. Y. Unno et al., ATLAS17LS – A large-format prototype silicon strip sensor for long-strip barrel section of ATLAS ITk strip detector, NIMA V989 (2021) 164928
2. L. Poley et al., The ABC130 barrel module prototyping programme for the ATLAS strip tracker, JINST (2020) 15 P09004
3. Y. Han et al., Study of CMOS strip sensor for future silicon tracker, NIMA V981 (2020) 164520
4. F. Ruehr et al., Testbeam studies of barrel and end-cap modules for the ATLAS ITk strip detector before and after irradiation, NIMA V979 (2020) 164430
5. Z. Liang, "Construction of the new silicon microstrips tracker for the Phase-II ATLAS detector", NIMA V924 (2019) 265-269
6. G. Villani, et al., OVERMOS - CMOS Hi-Res MAPS detectors for HEP applications, NIMA V924 (2019) 78-81
7. A. Blue, et al., Testbeam Evaluation of Silicon Strip Modules for the ATLAS Phase-II Strip Tracker Upgrade, NIMA V924 (2019) 108-111
8. W. Lu, et al., "Development of the ABCStar front-end chip for the ATLAS silicon strip upgrade", 2017 JINST 12 C04017
9. ATLAS CMOS Strip Collaboration, "Charge collection studies in irradiated HV-CMOS particle detectors", 2016 JINST 11 P0400

报告>20

10. E. Buchanan, "Testbeam studies of ATLAS ITk Strip modules at DESY-II", Beam Telescope and Test Beams Workshop, 8-11 February 2021, Lecce, Italy
11. P. Liu, "ATLAS Upgrade", CLCHP2020, 6-9 November, Beijing, China
12. Y. Han, "Study of the HV-CMOS active strip sensor (CHESS2) for future silicon trackers", 14-18 December, 2019, Hiroshima, Japan
13. 韩雨孛，"CMOS硅微条探测器研究进展"，高能物理大会，16-24 June, Shanghai, China
14. H. Zhu, "ATLAS Detector Upgrade", CLHCP2018, 19-22 December, 2018, Wuhan, China
15. X. Shi, "ATLAS Strip Tracker", International Workshop on the High Energy Circular Electron Positron Collider, 12-14 November, 2018, Beijing
16. X. Ai, "The Layout and Performance of the Phase-II upgrade of the tracking detector of the ATLAS experiment", Poster at IEEE NPSC-MIC, 21-28 October, 2017, Atlanta, USA
17. Z. Liang, "Construction of the new silicon microstrips tracker for the Phase-II ATLAS detector", HSTD11 & SOIPIX2017, 10-15 October, 2017, Okinawa, Japan
18. W. Lu, "Development of the ABCStar front-end chip for the ATLAS silicon strip upgrade", TWEPP, 26-30 September, 2016, KIT, Germany

人才培养

- 博士后：
  - Jason Mansour -》工业界
  - 刘义 -》DESY fellow
  - 艾小聪 -》DESY fellow
  - 修青磊-》散裂中子源
  - 杨玉真 -》上海中医药大学
  - 张晋 -》中山大学副教授
  - 张登峰 -》Sheffield U博士后
  - Emma Buchanan -》CERN fellow
  - 刘洋（在站）
  - 刘凯（在站）
  - Matthew Kurth（在站）
- 博士生：
  - 陈列建 -》华为
  - 韩雨李 -》DESY fellow
  - 李博洋-》
  - 张凯栗（在读）
  - 陈叶波（在读）
  - 李瞻（在读）

国际合作

学习借鉴、合作研发

- 与CERN、宾夕法尼亚大学等单位合作开展抗辐照ASIC芯片设计
- 与德国DESY围绕束流测试，DAQ软件、离线分析软件开发等研究工作
- 重点与英国卢瑟福实验室（RAL)及多所英国高校围绕硅微条探测器模块设计与建造开展深入合作，形成稳定的UK/China集群。

职工、博士后等轮流常驻RAL（2 FTE），合作完成原型样机等，掌握关键技术，为在国内成功试制样机奠定基础。

未来量产阶段，借用RAL设施生产500个模块，国内生产500个模块。

经费执行情况

项目	预算批复数	调剂后预算	审计认定支出数	审计认定结余数	应付未付认定数	审定净结余数
一、资金支出	1,345.00	1,345.00	1,337.92	7.08	5.38	1.70
（一）直接费用	1,168.00	1,168.00	1,160.92	7.08	5.38	1.70
1.设备费	48.00	40.31	40.31	0.00		0.00
（1）购置设备费	48.00	40.02	40.02	0.00		0.00
（2）试制设备费	0.00			0.00		0.00
（3）设备改造费	0.00	0.29	0.29	0.00		0.00
（4）设备租赁费	0.00			0.00		0.00
2、劳务费、专家咨询费、会议/差旅/国际合作交流费、其他支出	593.70	590.91	583.87	7.04	5.38	1.66
（1）劳务费	205.00	209.10	209.10	0.00		0.00
（2）专家咨询费	10.00	0.00	0.00	0.00		0.00
（3）会议/差旅/ 国际合作交流费	266.20	273.43	271.77	1.66		1.66
（4）其他支出	112.50	108.38	103.00	5.38	5.38	0.00
3、材料费、测试化验加工费、燃料动力费、出版/文献/信息传播/知识产权事务费	526.30	536.78	536.74	0.04		0.04
（1）材料费	482.80	479.33	479.33	0.00		0.00
（2）测试化验加工费	20.00	10.96	10.96	0.00		0.00
（3）燃料动力费	18.50	18.46	18.46	0.00		0.00
（4）出版/文献/ 信息传播/知识产权事务费	5.00	28.03	27.99	0.04		0.04
（二）间接费用	177.00	177.00	177.00	0.00		0.00
其中：绩效支出	0.00	52.52	52.52	0.00		0.00

执行率：99.8%

序号	单位名称	承担 / 参与	预算批复数	调剂后预算数	账面支出数	审计认定支出数	应付未付认定数	审定净结余数
1	中国科学院高能物理研究所	承担	1,241.60	1,241.60	1,234.68	1,234.68	5.38	1.54
2	清华大学	参与	103.40	103.40	103.24	103.24		0.16
合计			1,345.00	1,345.00	1,337.92	1,337.92	5.38	1.70

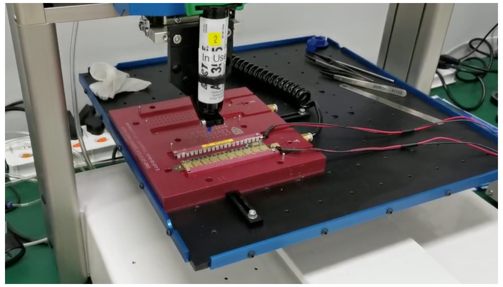
总结

- 高能所、清华大学参加外层硅微条探测器桶部项目（ITk-Strip）。通过科技部重点研发计划支持，顺利完成课题研究：
  - 前端读出电子学ASIC设计
  - 硅微条探测器模块设计
  - CMOS硅微条探测器性能研究
- 积极开展国际合作，掌握硅探测器制作基本工艺流程，确立量产任务。积累相关研发经验，培养人才队伍，为以后国内研制类似探测器奠定扎实基础。

感谢科技部大力支持！感谢专家莅临指导！

工艺流程 I

Hybrid控制板



平整度检查

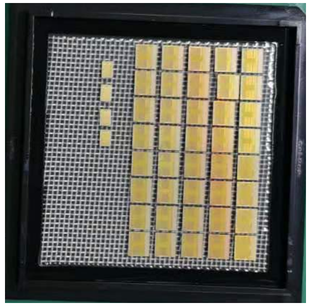
柔性PCB（+无源器件）

1. 自动点胶
2. 紫外凝固
3. 胶水厚度等测量
4. 后端打线

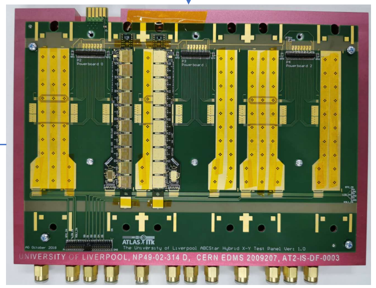
Hybrid

工装夹具加载（位置、间隙控制）

ABC/HCC芯片



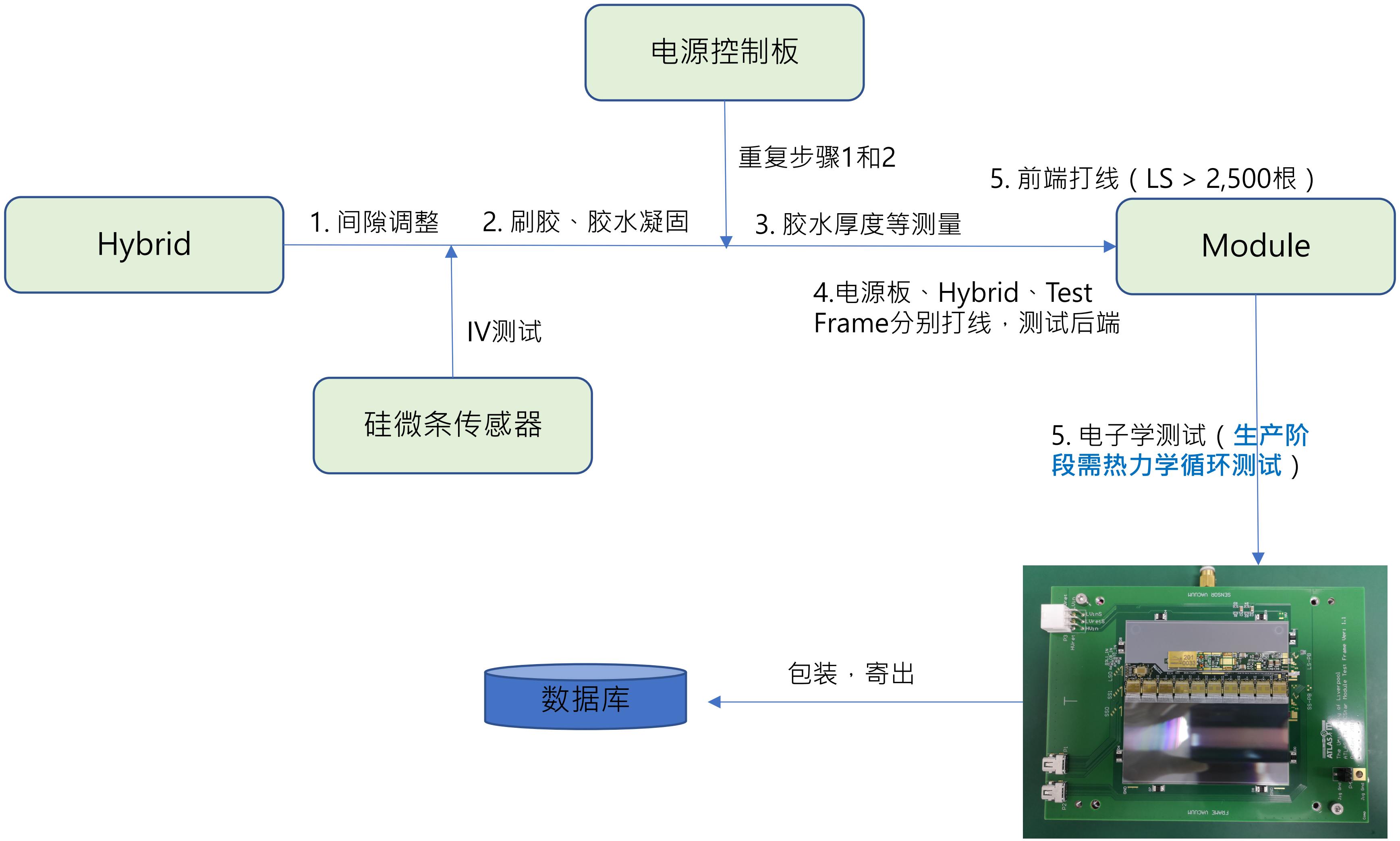
5. 电子学测试（+100小时恒温烘烤）



数据库

工艺流程 II

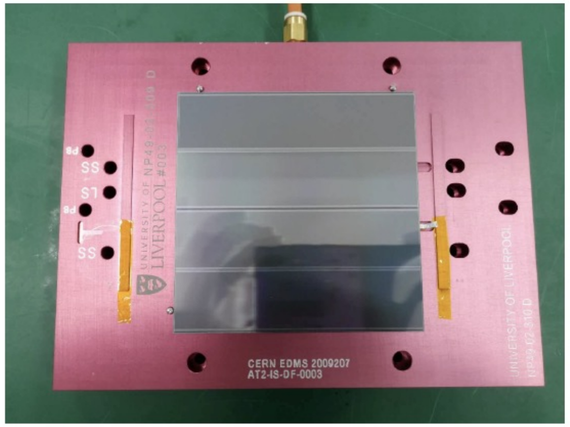
硅探测器模块



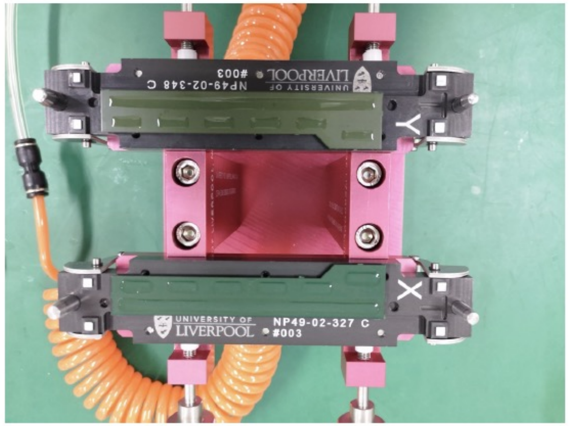
工艺流程 II

硅探测器模块

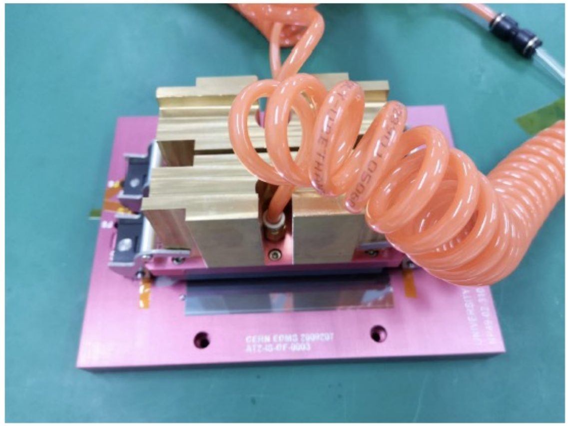
- Align Sensor on sensor plate



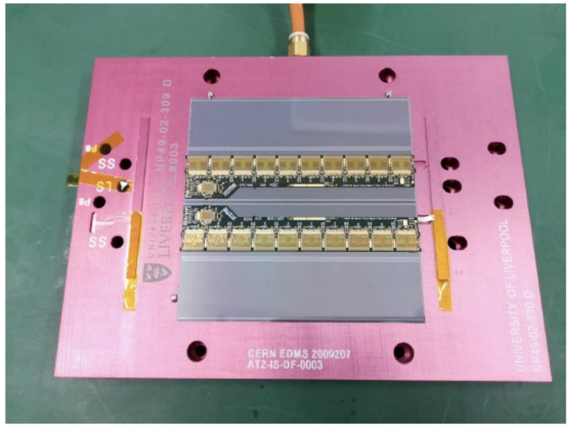
- Dispense glue on Hybrid through Stencil



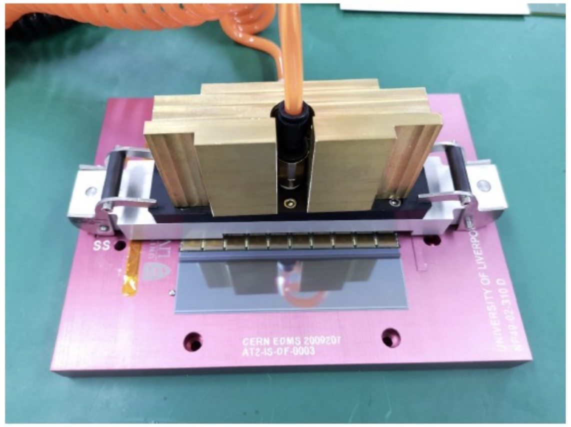
- Glue Hybrids on sensor



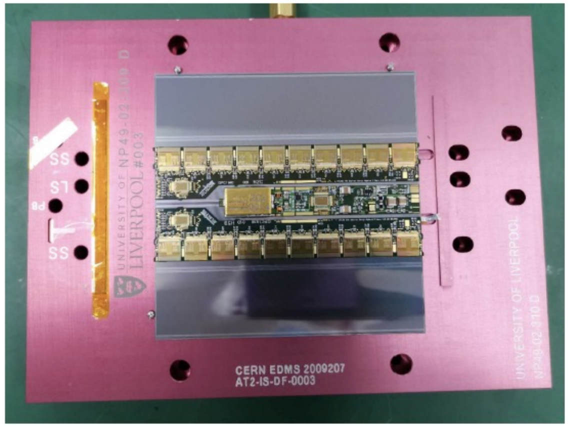
- Module without Powerboard



- Glue Powerboard to sensor



- Assembled Module



质量控制与确认

硅探测器模块

- 定义严格的质量控制（Quality Control）步骤，器件分批次质量确认（Quality Assurance）
- 形成规范文档（合作组审核）（EDMS文档管理系统），器件全程追踪（集中式数据库）

Assembly Procedures - Hybrids

Introduction	**1**
Manual assembly of hybrids	**3**
Industrial assembly of hybrids	**6**
After curing: Loading Hybrid in Burn-in panel	**8**
References	**8**
Appendix:	**9**
Step-by-step How-to Manual	**9**
Step-by-step How-to Industry	**10**
Database interactions for hybrids	**11**
Reception of components:	11
QC of components/assemblies (see figure below):	11
Hybrid assembly	12

Introduction

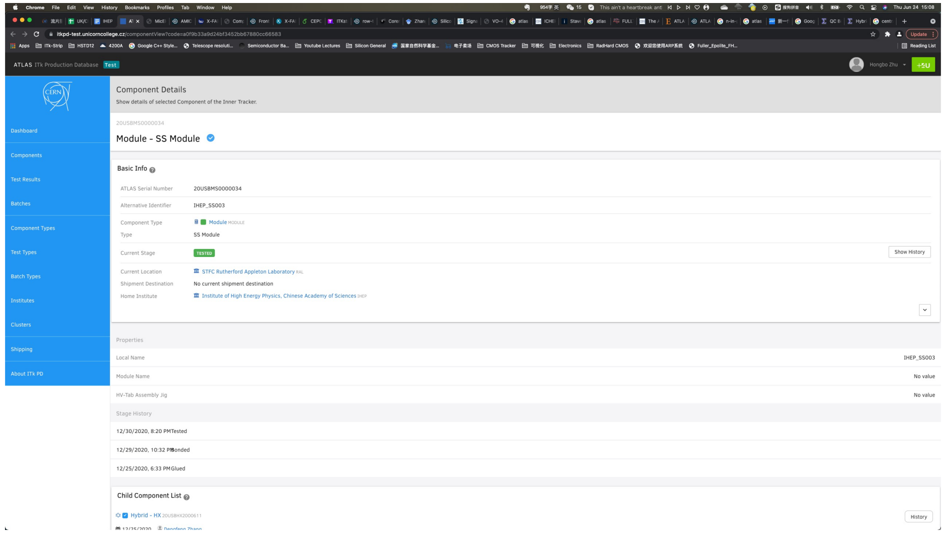
This document describes the procedure for gluing ASICs onto hybrids that have been assembled with SMD components (namely, a *stuffed hybrid*, or more precisely, an *SMD Stuffed Flex*). It covers both Barrel and Endcap assembly, with separate sections for manual and industrial assembly of hybrids. Steps that are common to both procedures are included in this introduction. Throughout this document, the term ASICs will be used when referring to both ABCStar and HCCStar chips.

Upon reception of hybrids and ASICs, a visual inspection will take place, and pictures will be taken in case of problems spotted. All components will have previously been registered in the database.

Hybrids: Please check the hybrid reception document for how to do reception tests on SMD-stuffed hybrids. This will include visual inspection, as documented in the visual inspection document. It is mandatory to check that the received hybrid flex matches the one registered in the database. It is assumed here that all materials (hybrids and ASICs) have passed bond pull testing requirements as described in the bond pull testing procedures (see wirebonding QC document and bond pull procedures).

The weight of the SMD stuffed hybrid, before and after ASIC attachment, is recorded in order to estimate the amount of glue applied, using a scale with a precision of at least 0.1mg. During pre-production, the weight of each hybrid is recorded. It is required to record

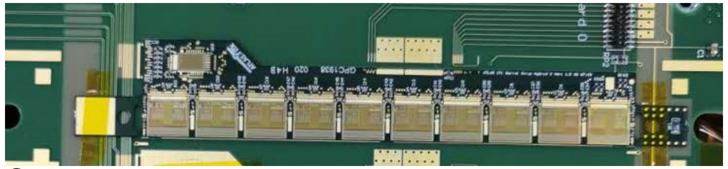
EDMS 2227803 | AT2-IS-EP-0053 v.5.2 status Released-Approved access Restricted
Assembly-Procedures_Hybrids.pdf modified 2021-06-22 15:22



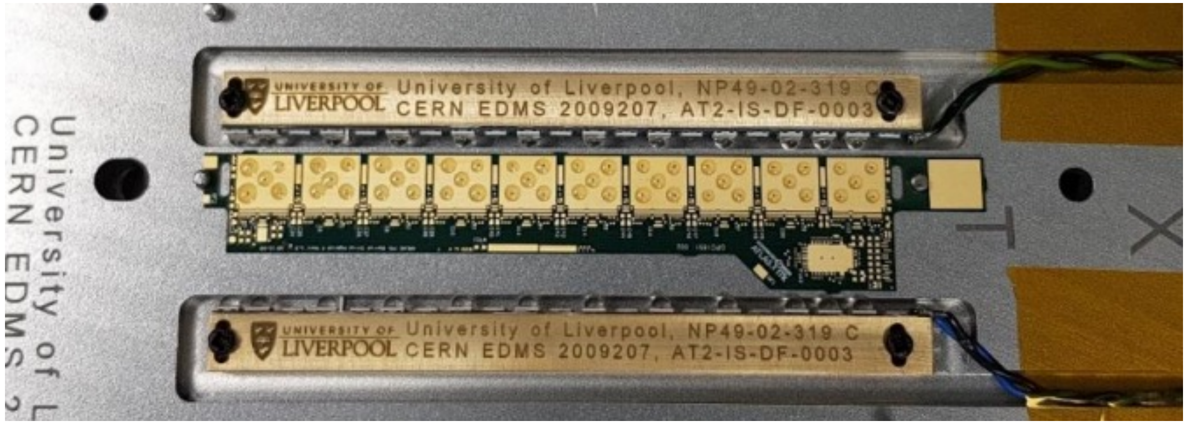
影像测量

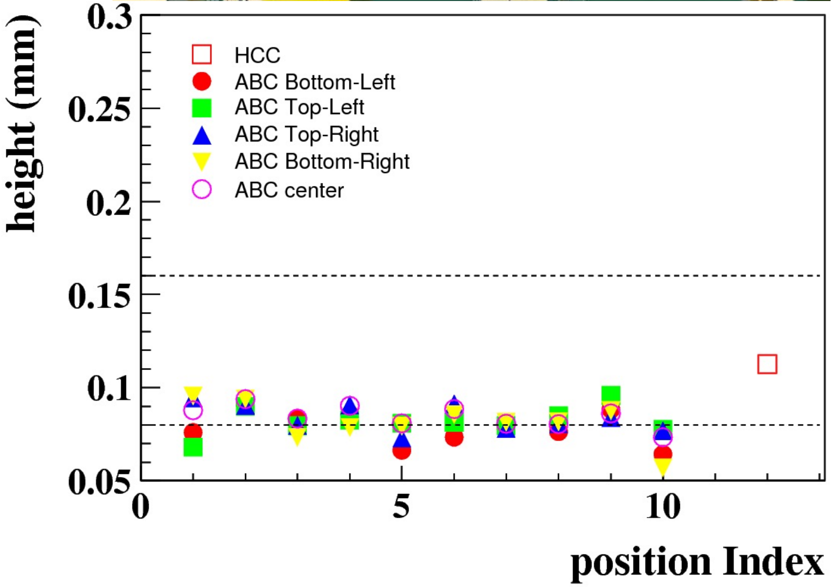
胶水厚度测量

- 用影像仪（SmartScope）激光或硬探针测量芯片与PCB之间胶水的厚度（要求范围120±40 um），工装夹具控制间隙
  - 过高会导致等量胶水情况下，芯片上胶水覆盖面积不足，影响散热
  - 过低会出现胶水从芯片下方溢出，影响后续打线



银胶改成紫外凝胶，缩短凝固时间，提升生产效率

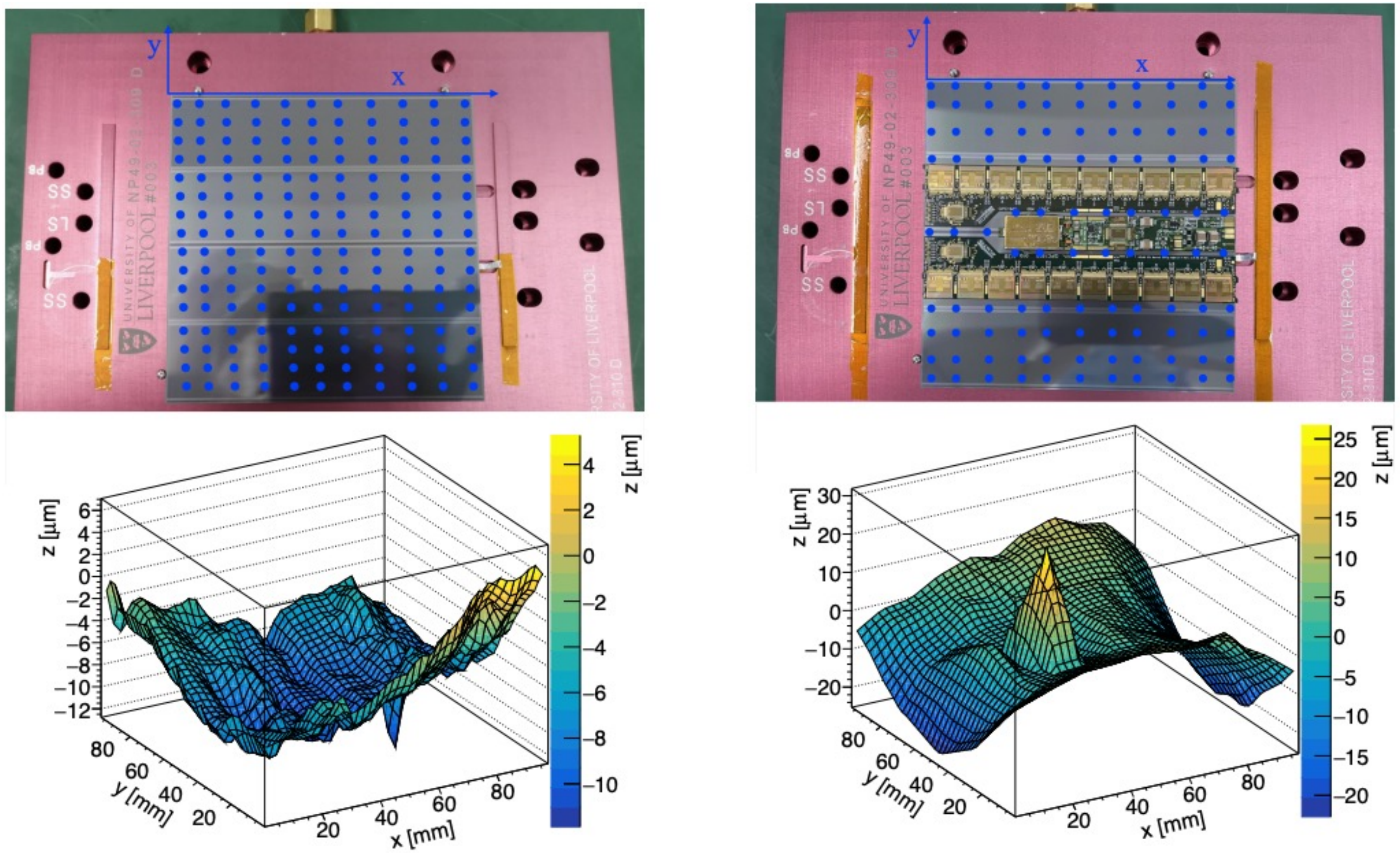




影像测量

传感器平整度测量

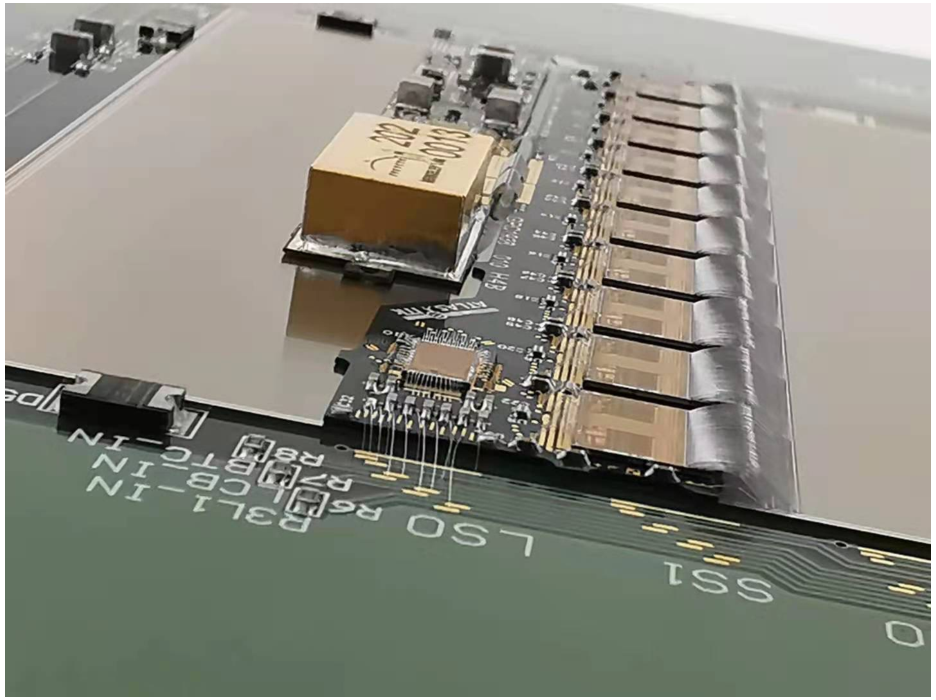
- 用影像仪测量传感器加载Hybrid和电源控制板前后弯曲/平整程度



引线键合

高密度打线

- 探测器模块打线总数（SS: >5,000 LS: > 2,500），需要仪器长时间高速、稳定运行 → 高效运行程序，修复坏线
- 芯片与传感器之间四层高密度引线



BJ820

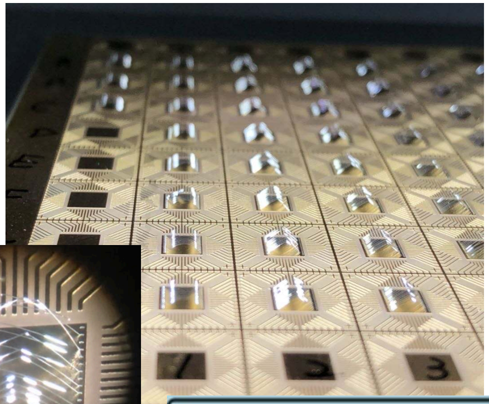
引线强度

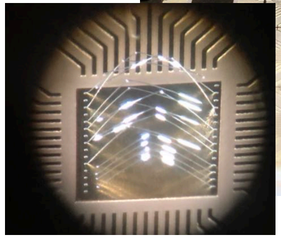
推拉力测试

BJ20

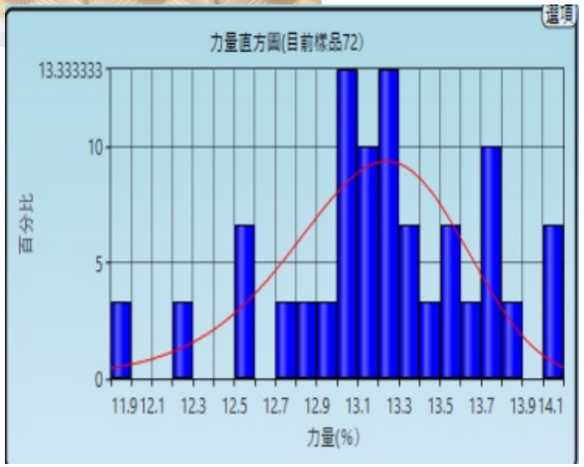
- 推拉力测试机测定引线的强度及损坏方式，相应调整打线机的参数（考虑焊板材质等因素）或是更换劈刀后重新确认参数

Dage 4000 Plus





专用练习板
每组线代表一组邦定机参数（优化提高引线质量）

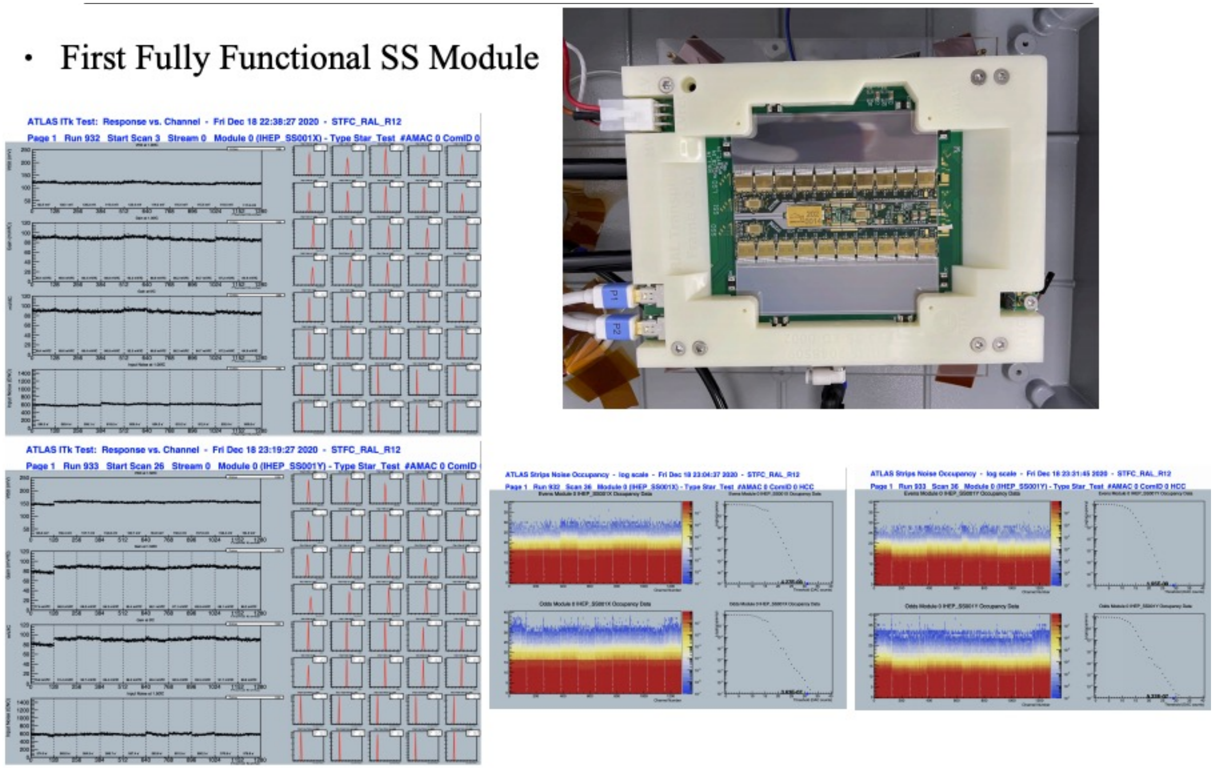


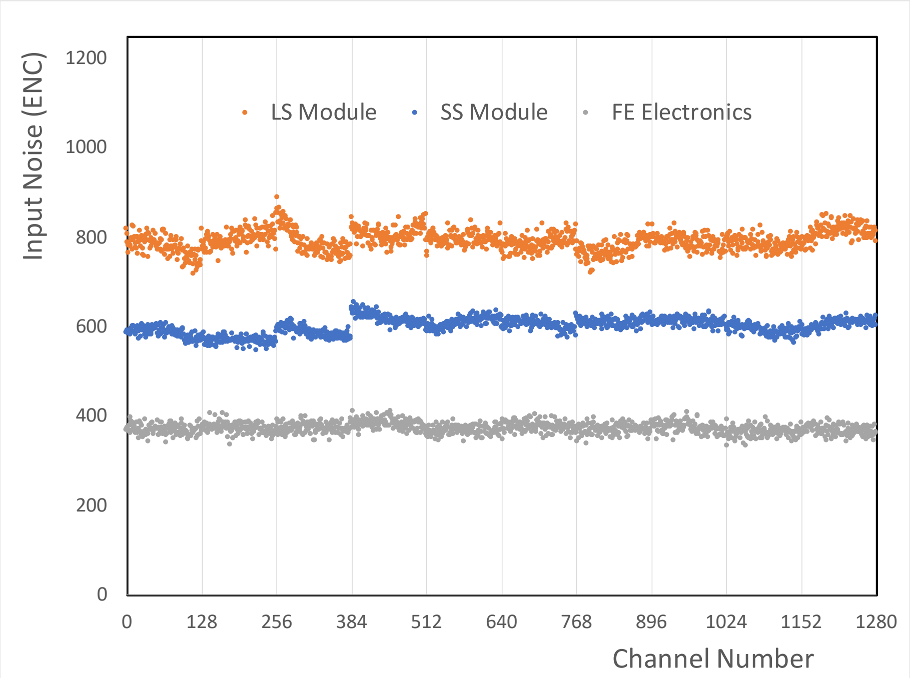
引线强度与打线参数、焊盘材质相关

电子学测试

噪声水平测试

- 确认模块（芯片+传感器）工作正常，测定增益、噪声水平等
  - Pedestal Scan → Strobe Delay Scan → 3 Point Gain → Trim Range → Response Curve → Noise Occupancy





加载LS/SS模块前后电子学噪声变化

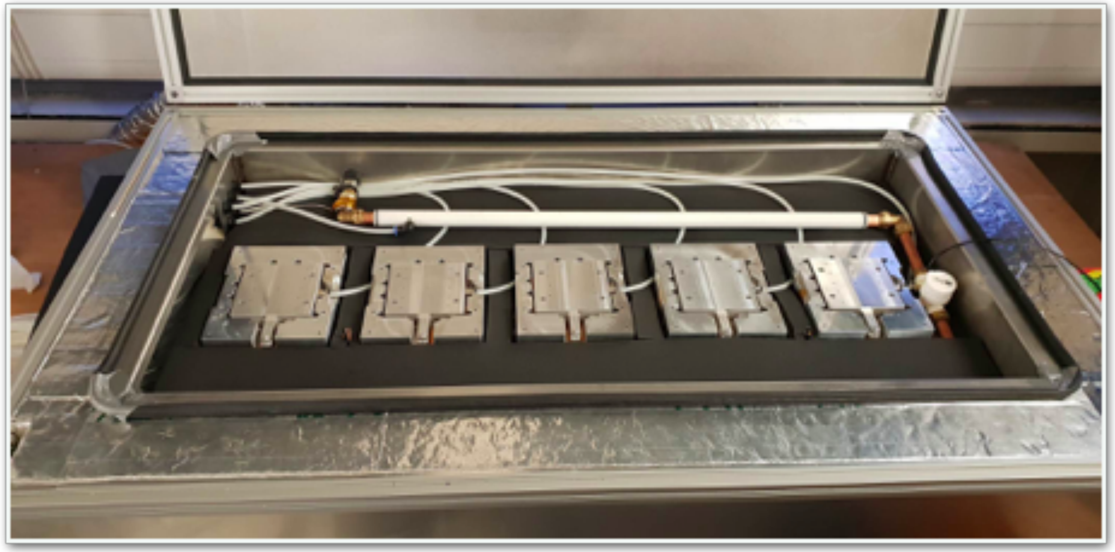
热力学循环测试

器件可靠性

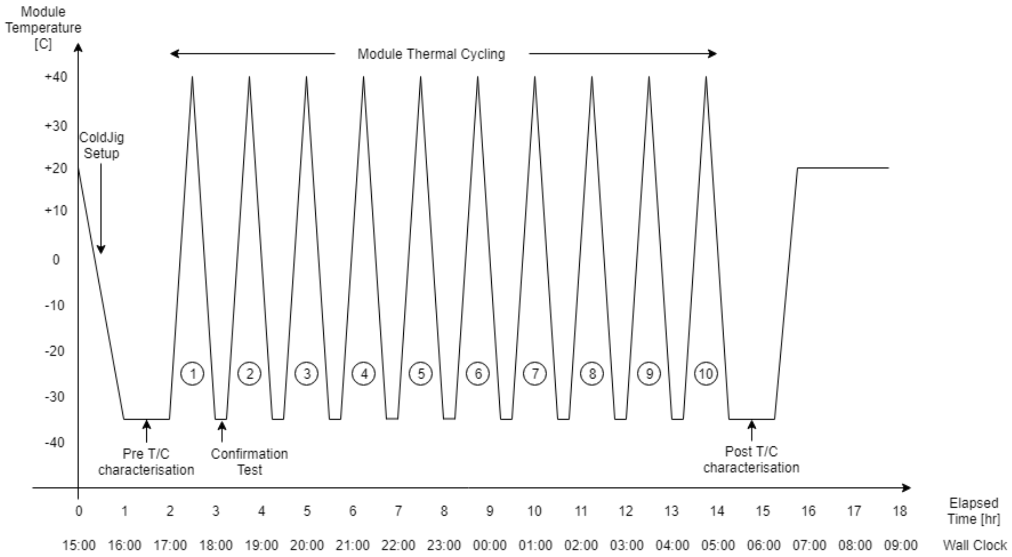
- 复合PCB老炼（Burn-in）：在40^0C条件下，连续测试100小时

- 模块热力学循环测试（Thermal Cycling）：5个模块同时测试，20小时内完成10次-35 ^{0}C 至 +40 ^{0}C 循环测试。

冲氮气或干燥空气保持低湿度，防止冷凝

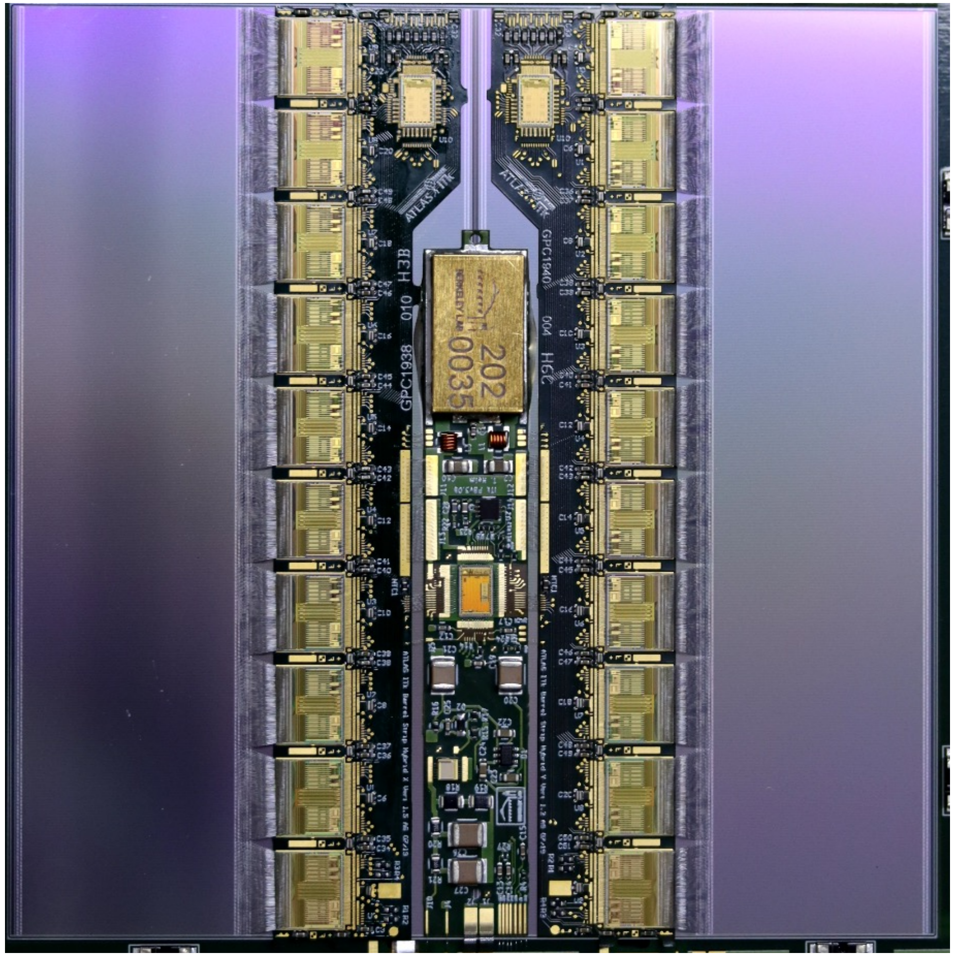


阶段性测试，确保模块正常工作

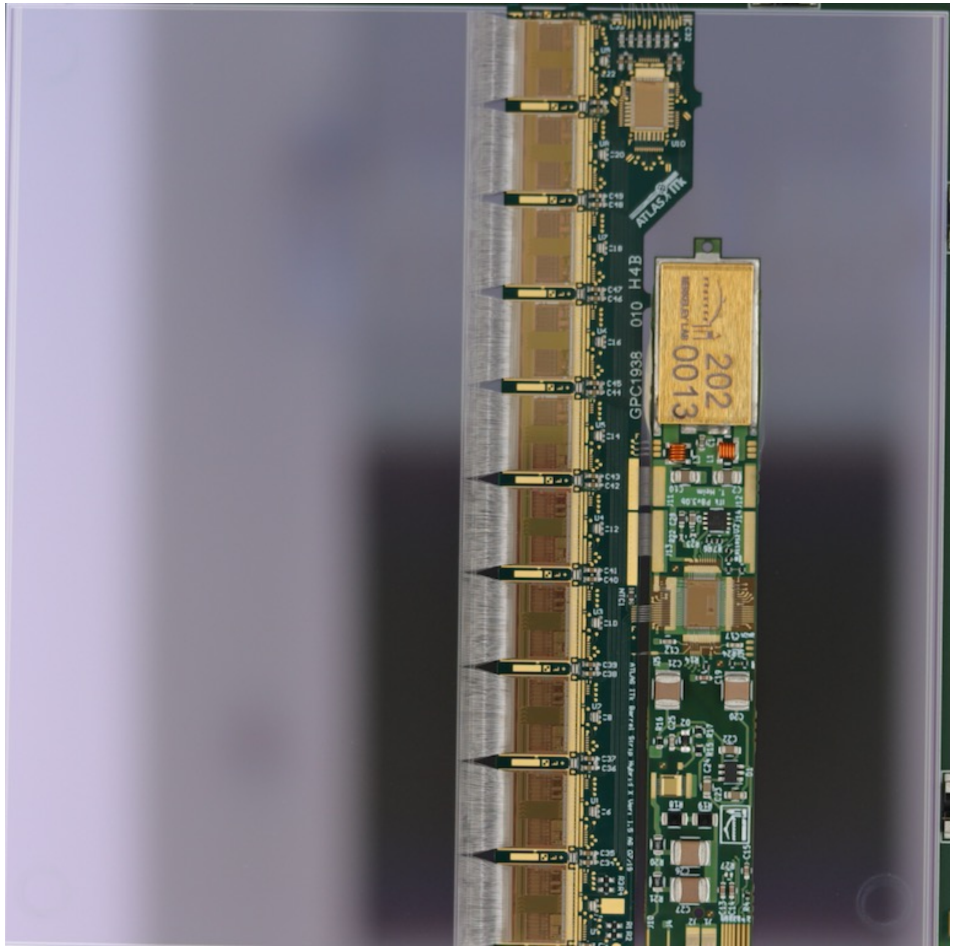


模块样机

LS/SS模块



SS Module （ 3/3 ）

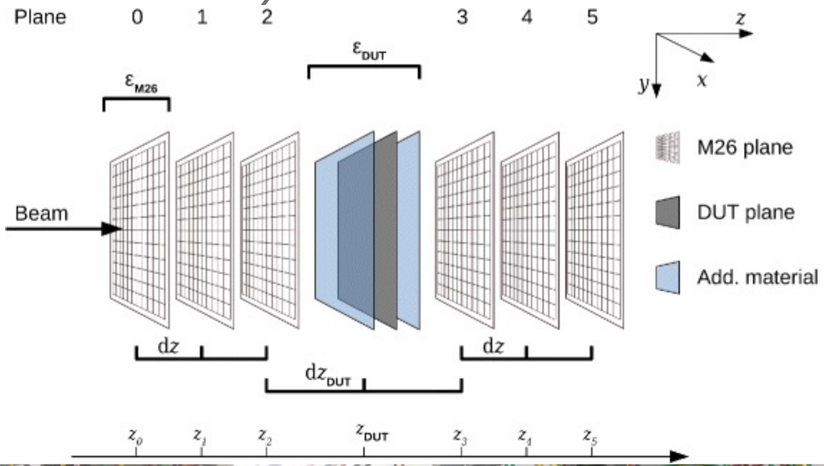


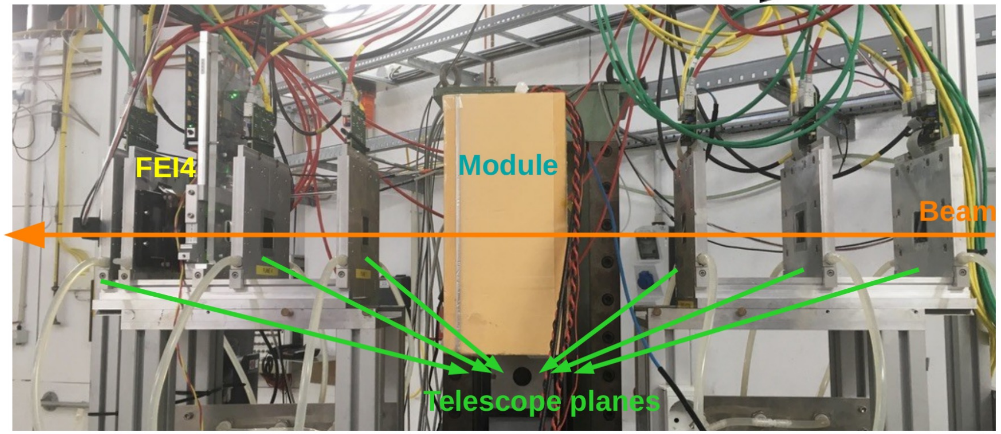
LS Module (2/3)

束流测试

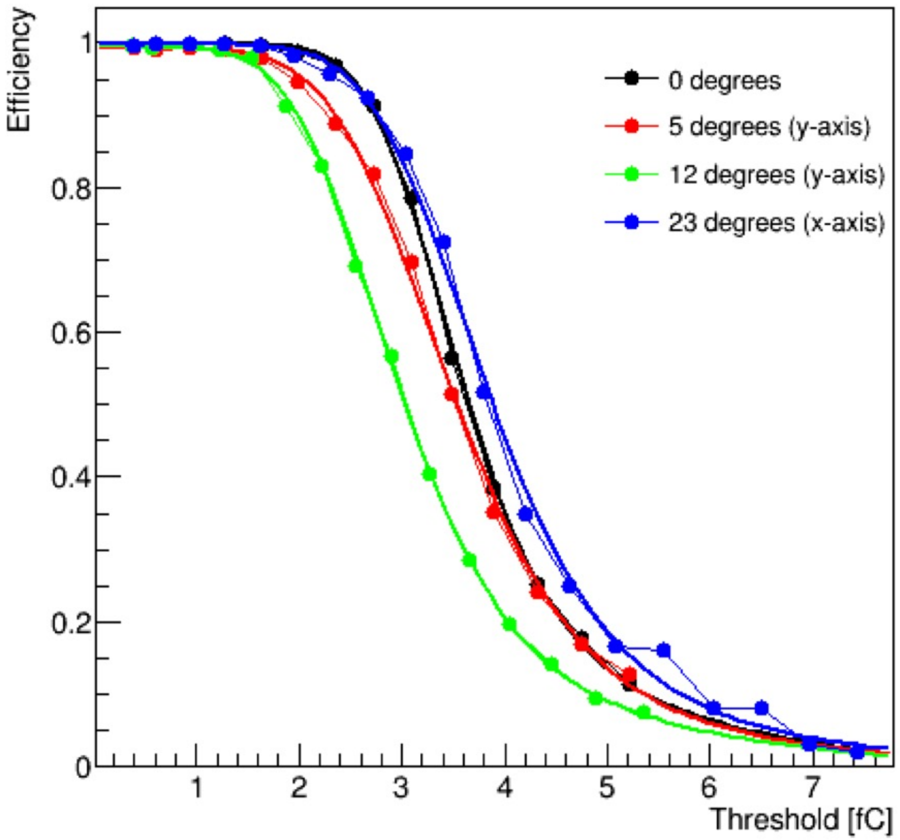
位置分辨率、探测效率等

- 标定探测器位置分辨率、探测效率等，测试数据获取系统（最接近实验的探测器运行环境）





表征电荷量/电荷共享随入射角度变化



传感器小样片测试

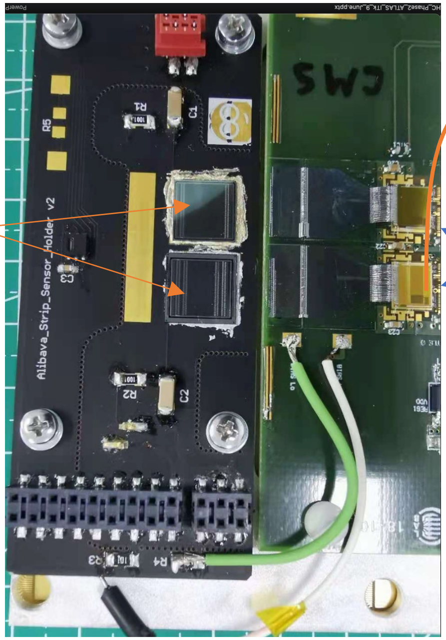
ALIBAVA 读出系统

传感器用探针台结合LCR源表/半导体特征分析仪提取特征参数外

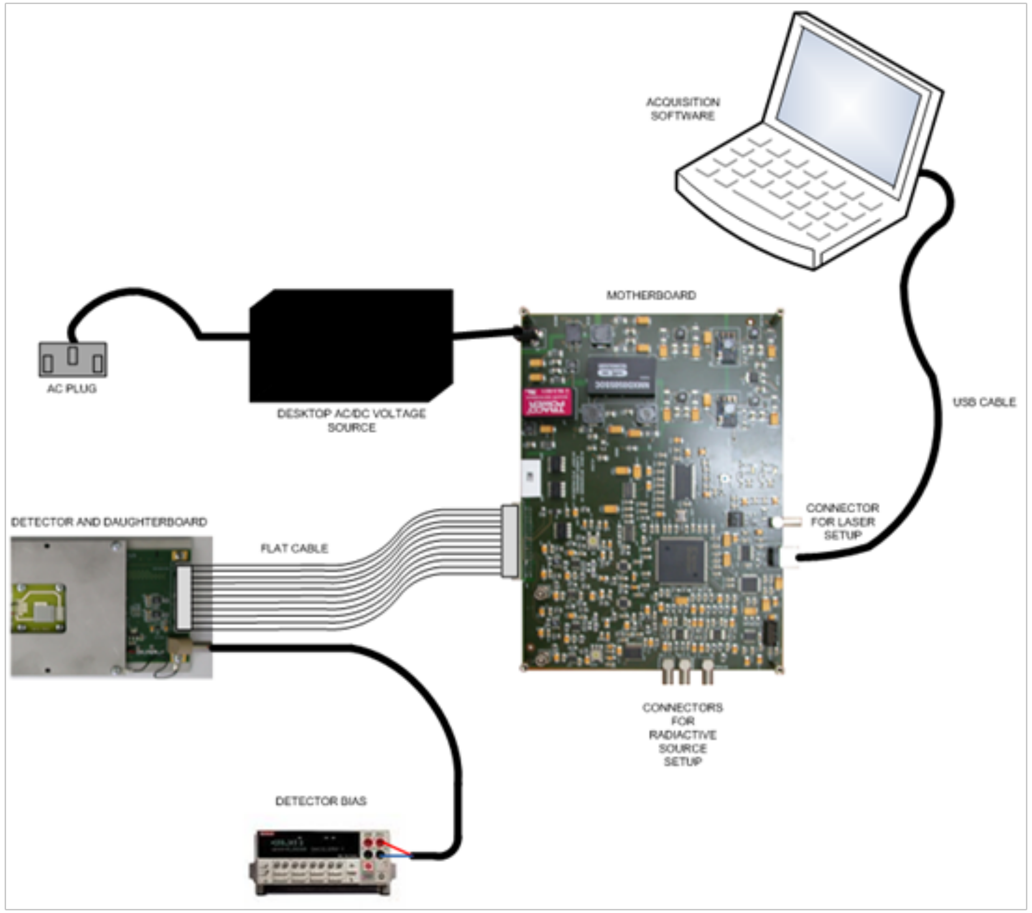
- 商用读出系统，最多支持256通道，子板两片LHCb实验用Beetle芯片（128通道模拟/数字读出）

Detector Board　　Daughter Board

Mini Sensor



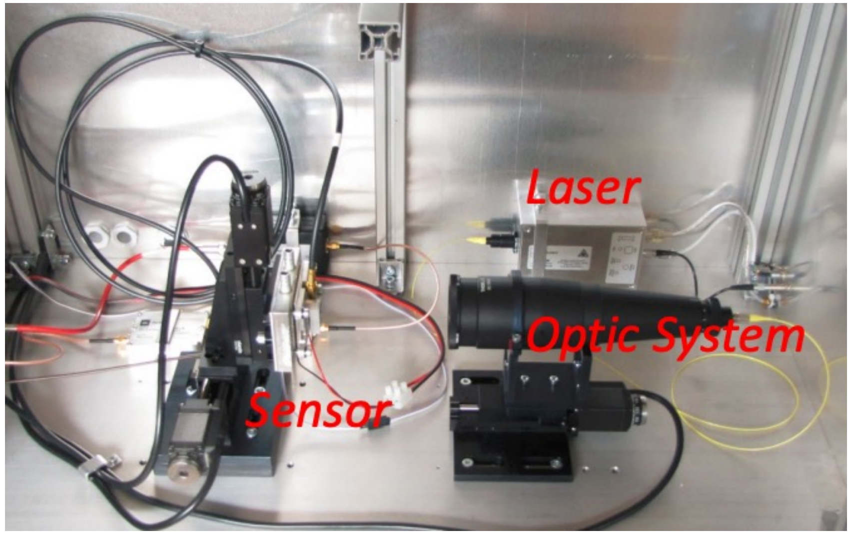
Beetle芯片

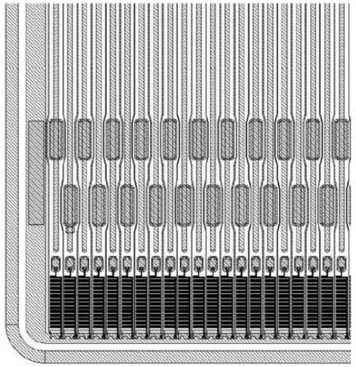


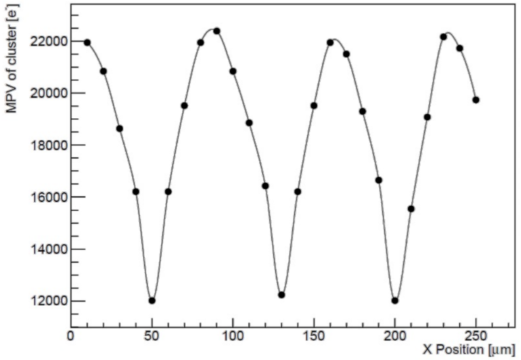
激光、放射源测试

样片基本性能

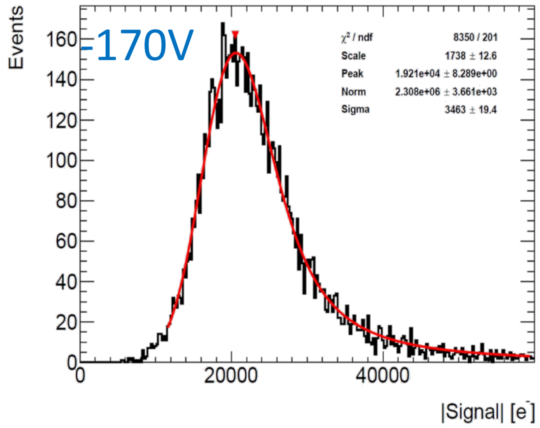
- 激光（红光/红外）测试传感器响应

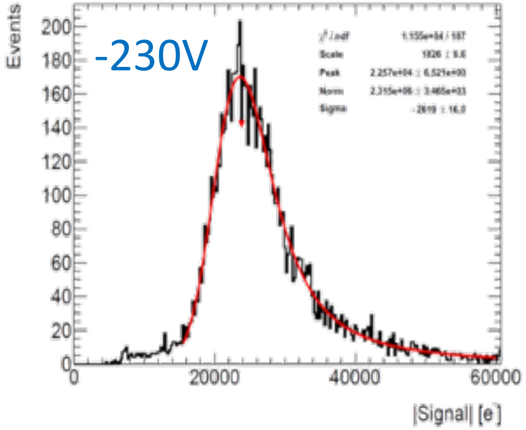


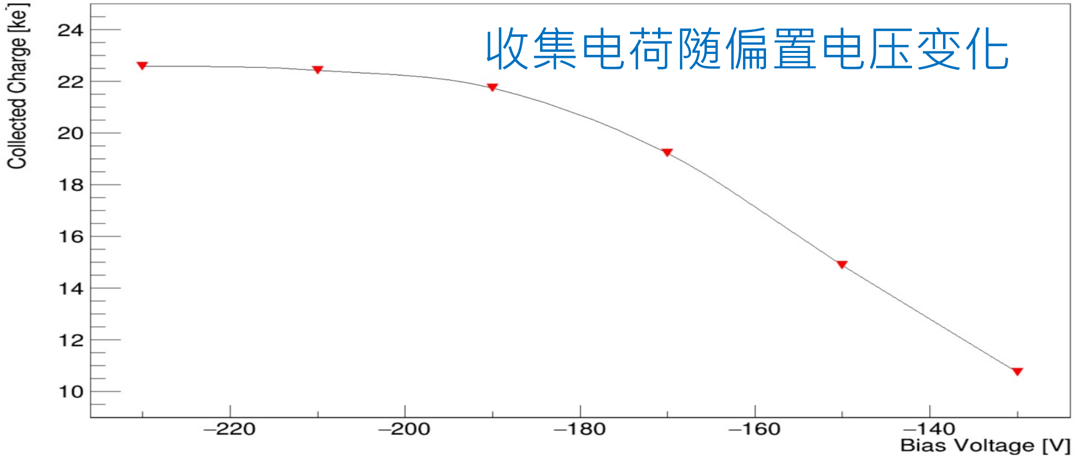




- Sr-90（ “近似最小电离粒子” ）测试电荷收集

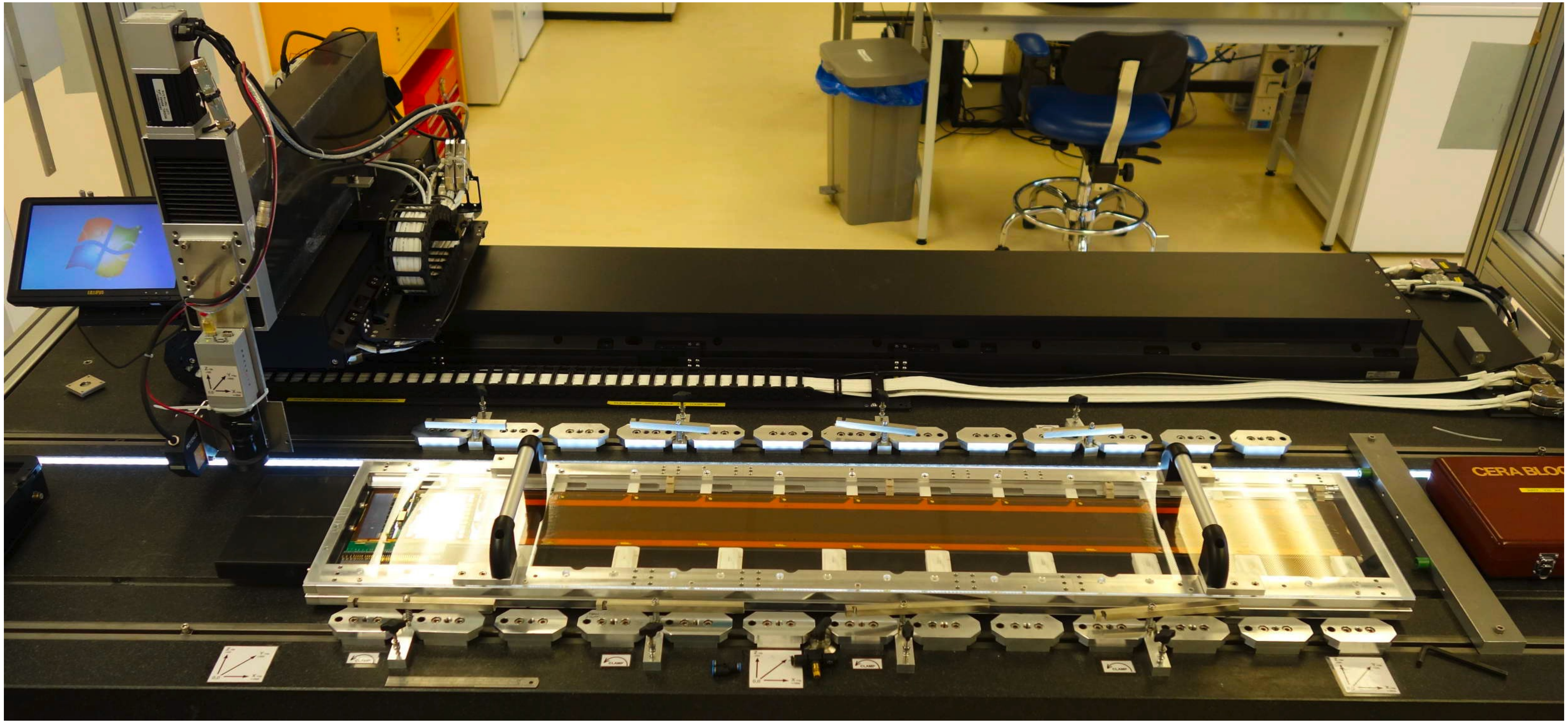






模块加载

- Gantry system



系统结构

- Stave System Architecture Diagram